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FREE FLOODED HIGH POWER MAGNETOSTRICTIVE TRANSDUCER MODEL PROGR--ETC(U)
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Free Flooded High Power Magnetostrictive Transducer Model Program.

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THE BENDIX CORPORATION
Pacific Division
North Hollywood, California

055 125

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INTRODUCTION

Bureau of Ships Contract NObsr-89245 (FBM) as modified includes the construction and test of 1500 Hz and 750 Hz transducer models and the design of a low frequency transducer to meet the requirements of specifications established in No. 689A-0399 "Design Objectives for High Power Low Frequency Transducers".

This report covers the work done on 1500 Hz and 750 Hz transducer models to establish the design necessary to meet the specified objectives.

Tests on small 6000 Hz free flooded magnetostrictive scroll transducers, with no pressure release material, indicated electro-acoustic efficiencies greater than 50 percent could be achieved with performance independent of depth.

The advantages are:

1. The scroll type transducer is simple in construction. Each scroll is a strip of nickel wound to form a laminated ring of the desired sizes and bonded together with an epoxy adhesive.

2. When proper tooling has been set up, scrolls can be reproduced at low cost, dimensions are easily controlled, and repeatability is assured.

3. The scrolls are mechanically rugged and cannot be damaged by over driving. Electrical breakdown is limited only by the insulation on the wire.

Section 1

DESIGN OBJECTIVES

The design objectives are:

1. Frequency

    1500 Hz models
    750 Hz models

2. Bandwidth

    Optimum

1500 Hz model	1285-1715 Hz
750 Hz model	643-857 Hz

    Minimum

1500 Hz model	1370-1630 Hz
750 Hz model	685-815 Hz

3. Acoustic Power Output

    Optimum

1500 Hz model	2.19 kw
750 Hz	8.75 kw

    Required

1500 Hz model	1.56 kw
750 Hz model	6.25 kw

4. Depth not limited.

5. Directivity Index 0 to 3 db

6. Efficiency

Optimum	80 percent
Minimum required	50 percent

7. Physical Structure

    A base plate must be provided to prevent the transducer from sinking in a muddy bottom. The overall size and weight should be the minimum practicable.

Section 2

EXPERIMENTAL DEVELOPMENT

All scrolls used in these experiments were made of cobalt nickel strip bonded with an epoxy adhesive.

Dimensions are shown in Figure 1. The scroll height is the width of the nickel strip. The scroll thickness is determined by the strip thickness and the number of turns.

DOSS 1-8 1500 Hz MODEL ASSEMBLIES

Eight scrolls were assembled in various combinations of two to eight scrolls to determine the effect of stack height, mounting, spacing between scrolls, wall thickness and wire to establish the design data necessary to meet the specification requirements.

Scroll dimensions are:

Scroll mean diameter:	26.64 inches
Scroll height:	0.90 inch
Scroll thickness:	0.50 inch

The scroll material is: 0.010 inch thick 204 nickel strip

Figure 2 shows a typical assembly and test fixture.

DOSS 1-8 TESTS

Effect of Mounting

Two scrolls, with a 1/8 inch thick and 1/2 inch wide neoprene strip cemented to each edge, were stacked and a loose winding of 200 turns of No. 14 stranded polyethylene insulated wire was installed. The polarizing current was 10 amperes dc.

f_r = 1670 Hz $\quad$ Q_{mw} = 4.3 $\quad$ Efficiency: 7.5 percent

(See Appendix 2 for symbol definitions)

The neoprene strip was removed from the scroll edges and the two scrolls were separated by six equally spaced neoprene blocks 1/8 inch thick, 1/2 inch wide, and 1 inch high. The winding was supported from the scrolls by fiberglas rings spaced 1 inch from the scroll edges by six neoprene blocks 1 inch thick, 1/2 inch wide and 1 inch long.

f_r = 1890 Hz $\qquad$ Q_{mw} = 24 $\qquad$ Efficiency = 17 percent

(Figure 3 is the impedance in water with and without the neoprene on the scroll edges.

(Figure 4 is the transmitting response with and without the neoprene on the scroll edges.)

Effect of Scroll Stacking

Stacks of two, three, four and eight scrolls were assembled with six equally spaced 1/8 inch thick, 1/2 inch wide and 1 inch high neoprene blocks between scrolls. A 200 turn winding was supported by fiberglas rings spaced 1 inch from the scroll edges by six neoprene blocks 1 inch thick, 1/2 inch wide and 1 inch high. The polarizing current was 10 amperes dc. (Figure 5 is the impedance of the assemblies, Figure 6 the transmitting response, Figure 7 a typical azimuth pattern, and Figure 8 a typical vertical pattern.)

Number of Scrolls	f_r Hz	T	RΩ	Q_{mw}	Eff.
2	1890	81.0	46	16.5	17%
3	1780	85.2	55	21	31%
4	1730	87.0	56	16.5	46%
8	1610	87.2	45	7.2	60%

Effect of Scroll Spacing

Four scrolls were assembled with six equally spaced 1/8 inch thick, 1/2 inch wide and 1 inch long neoprene blocks between the scrolls. A 200

turn winding was supported by fiberglas rings spaced 1 inch from the scroll edges by six neoprene blocks 1 inch thick, 1/2 inch wide and 1 inch long. An identical assembly was mounted with a space of 3-1/2 inches scroll edge to scroll edge. The windings were connected in series. The polarizing current was 10 amperes dc.

f_r = 1730 Hz R = 70Ω T = 89.5 Q_{mw} = 12.4 Eff. = 64%

The fiberglas rings were removed from one edge of each scroll assembly and the assemblies spaced 1-1/8 inches with a single 200 turn winding common to both assemblies and supported by fiberglas rings.

f_r = 1700 Hz R = 58Ω T = 88.5 Q_{mw} = 9.7 Eff. = 63%

The spacing between assemblies was reduced to 1/8 inch (all 8 scrolls spaced 1/8 inch).

f_r = 1610 Hz R = 45Ω T = 87.0 Q_{mw} = 7.5 Eff. = 58%

Effect of Scroll Thickness

The scroll wall thickness was reduced from 0.5 inch to 0.4 inch by removing ten layers of nickel from the ID of the scrolls. Eight scrolls, 0.4 inch thick, were assembled as stated above (1/8 inch spacing).

1. With 0.5 inch wall thickness

   f_r = 1610 Hz Z = 45 + j43 T = 87.0

   Q_{mw} = 7.5 Eff. = 58%

2. With 0.4 inch wall thickness

   f_r = 1530 Hz Z = 40 + j26 T = 86.3

   Q_{mw} = 8.5 Eff. = 55%

   (Figure 9 shows the impedance circles and Figure 10 the transmitting response curves.)

Effect of Stranded vs. Solid Wire

The eight scroll assembly discussed immediately above was rewound with No. 14 solid copper polyethylene insulated wire.

1. With stranded wire

$$f_r = 1530 \text{ Hz} \quad R = 40 \quad T = 86.5$$

2. With solid wire

$$f_r = 1530 \text{ Hz} \quad R = 38 \quad T = 87.0$$

High Power Tests

The eight scroll assembly discussed under 2 above was driven at high power with and without dc polarizing.

1. With dc polarizing

   (Figure 11 is the transmitting response at several power levels with 10 amperes dc polarizing and Figure 12 is the transmitting response at several power levels with 15 amperes dc polarizing.)

2. Without dc polarizing

   (Figure 13 is the source level from 1500 to 1800 Hz when unpolarized and driven from 750 to 900 Hz with an input of 5 amperes ac, and Figure 14 is a power curve when operated unpolarized. Driving frequency is 855 Hz, output is 1710 Hz.)

SUMMARY OF RESULTS FOR THE DOSS 1-8

The physical mounting of the individual scrolls has a great influence on the performance of the array. When two scrolls were spaced 1/4 inch with continuous 1/8 inch neoprene strips on the scroll edges the resonant frequency was 1670 Hz, Q_{mw} was 4.3 and the efficiency was 7.5 percent. When the neoprene strips were removed and the scrolls spaced 1/8 inch by small neoprene pads the resonant frequency was 1890 Hz, Q_{mw} was 24 and the efficiency was 17 percent.

When the number of scrolls in an assembly is increased the resonant frequency and Q_{mw} decreases and the efficiency increases. When the separation between scrolls is decreased the resonant frequency and Q_{mw} decreases.

There is no noticeable change in performance when using stranded or solid wire.

Efficiences of 50 percent or greater can be achieved when operating either with polarizing current or operating unpolarized as a frequency doubler. When operating unpolarized, efficient operation is achieved only at high power levels.

The lowest Q_{mw} of 7.2 was achieved with the eight scroll close spaced assembly. More model study is necessary to determine an assembly that will meet the requirements of a Q_{mw} of 5 or less.

Section 3

DOSS 2 AND DOSS 3 - 1500 CYCLES/SEC TRANDSUCER MODELS

DOSS 2 and DOSS 3 are transducer with scrolls, support structure and base plate, to scale the planned low frequency transducer.

DOSS 2

The DOSS 2 is an array of 12 scrolls mounted in three groups of four scrolls each. (Figure 15 is a photo of the DOSS 2 assembly.) The scrolls within each group are separated by six equally spaced 1/8 inch thick, 1/2 inch wide and 1 inch long neoprene pads. Each group is wound with 493 turns of No. 14 Polyethylene insulated wire supported on fiberglass rings spaced 1/2 inch from the scroll edges.

The spacing between groups is 2-1/2 inches, scroll edge to scroll edge. The windings are connected in series. The total active element height is 17 inches.

Scroll dimensions are:

Scroll diameter:	26.3 inches
Scroll height:	0.9 inches
Scroll thickness:	0.22 inches

They are made of 0.010 inch thick 204 nickel strip.

Measurements with 5 Amperes DC Polarizing

Figure 16 is the impedance, Figure 17 the vertical pattern at frequencies about resonance, and Figure 18 is the source level with input currents of 1 to 7 amperes ac.

f_r = 1520 Hz R = 165 ohms T = 92.5 db Q_{mw} = 9.1

The efficiency, with 4100 watts input was 45 percent.

Measurements Without DC Polarizing

Figure 19 is the source level from 1200 to 1800 Hz, when driven at 600 to 900 Hz, with an input current of 6 amperes ac.

Figure 20 is a power curve with measurements taken at the frequency of maximum output. The driving frequencies are 1/2 the output frequencies.

f_r = 1520 Hz T = 90.6 db Q_{mw} = 8 Eff. = 45 percent

DOSS 3

The DOSS 3 is an array of six scrolls mounted in three groups of two scrolls each. The two scrolls within each group are separated by six equally spaced 1/8 inch thick by 1 inch wide neoprene pads.

The electrical winding is supported by fiberglass rings spaced 1/2 inch from the scroll edge. The spacing between groups is 2-1/2 inches scroll edge to edge.

Each of the three groups is wound with 486 turns of No. 14 polyethylene insulation wire and the windings series connected.

The total active element height is 16 inches.

Scroll dimensions:

Scroll diameter:	26.3 inches
Scroll height:	1.8 inches
Scroll thickness:	0.42 inches

Material: 204 nickel strip 0.010 thick. (Figure 21 is the DOSS 3 assembly with mounting base.)

The polarizing current was 5 amperes dc

f_r = 1580 Hz T = 93.8 Q_{mw} = 5.5

(Figure 22 is the source level 1200 to 2000 Hz with 5 amperes dc polarizing and inputs of 1, 2, 4 and 5 amperes ac.)

(Figure 23 is the source level when driven unpolarized with 6 amperes ac input, and Figure 24 is a power curve with the source level measured at the frequency of maximum sound pressure for each input current when driven unpolarized.)

The scroll thickness was reduced from 0.42 inch to 0.32 inch. Vertical and azimuth patterns and transmitting response were measured without mounting base and with the mounting base spaced 6-1/2 inches and 10-1/2 inches from the transducer end.

There was no significant change with or without mounting base.

f_r = 1500 Hz T = 92.5 R = 150Ω Q_{mw} = 5.2 Eff. = 60 percent

(Figure 25 is the vertical pattern at resonance and at approximately -3 db.)

The azimuth patterns are circular at these frequencies.

(Figure 26 is the vertical pattern at 2610 Hz, Figure 27 is the impedance in water with 5 amperes dc polarizing, Figure 28 is the source level 1200 to 2000 Hz, Figure 29 is the transmitting response from 1000 to 10,000 Hz as measured off the side, Figure 30 is the transmitting response from 1000 to 10,000 Hz as measured of the end, and Figure 31 is the source level measured at the frequency of maximum sound pressure for each input current when driven unpolarized.)

The transducer was assembled with the spacing between pairs of scrolls reduced from 2-1/2 inches to 5/8 inches and a single winding of 465 turns, common to all scrolls, supported on fiberglass rings at each end of the transducer.

The total active element height was 12 inches.

The polarizing current was 5 amperes dc.

f_r = 1360 Hz R = 98 T = 90.5 Q_{mw} = 4 Eff. = 60 percent

(Figure 32 is the impedance in water, Figure 33 is the response 1000 to 3000 Hz, Figure 34 is the source level 1000 to 2000 Hz with inputs of 1, 2, 4 and 5 amperes ac, Figure 35 is the source level measured at the frequency of maximum wound pressure for each input current when driven unpolarized.)

SUMMARY OF RESULTS FOR THE DOSS 3

There is no measureable change in performance with the base plate mounted. Response measurements over a broad frequency range (1 to 10 kc) indicate several transducer cavity resonances. These cavity resonances effect the response and patterns as shown by Figures 26, 29 and 30, and make the transducer performance unpredictable at frequencies above about 2500 cycles/sec.

The vertical patterns are symmetrical at frequencies near resonance, as shown in Figure 25.

The azimuth patterns are circular at these frequencies. The 12 inch high, close spaced array with 0.32 inch wall thickness meets the design objectives of Q_{mw} less than 5, efficiency greater than 50 percent and power output greater than 1.56 KW.

Section 4

DOSS 4.1 - 750 CYCLE/SEC MODEL

The DOSS 4.1 transducer was scaled directly from the DOSS 3 close spaced six scroll array.

Six scrolls were mounted in groups of two scrolls each. The scrolls in each group were separated by three equally spaced neoprene pads 3/16 inch thick, 9/16 inch wide and 1 inch long. The pairs of scrolls are spaced 7/8 inch by three equally spaced support arms with neoprene pads on the contacting surfaces.

The winding was 800 turns of No. 16AWG, polyethylene insulated, copper wire. The winding was common to all scrolls and supported at the top and bottom by fiberglass rings. The total active element height was 21-3/4 inches and the active element weight was approximately 530 pounds.

Scrolls dimensions:

Mean diameter	47.5 inches
Height	3.25 inches
Thickness	0.57 inch

Material: 0.017 inch thick 204 nickel strip.

(Figures 36 and 37 show the complete transducer mounted for tests.)

DOSS 4.1 TESTS

Figure 38 is the impedance in water with 3.75, 5.0 and 7.5 amperes dc polarizing (10 to 20 oersted, and Figure 39 is low level transmitting response when polarized at 20 oersted).

f_r = 750 Hz T = 96.5 db R = 340 ohms Q_{mw} = 4.6 Eff. = 68%

The 800 turn winding was divided in half and the two halves connected in parallel, to reduce the voltage on the winding during high power measurements.

(Figure 40 is the impedance in air with the 400 turn winding and 20 oersted polarizing, and Figure 41 is the impedance in water measured by filtering the voltage and current and measuring the phase angle.)

The structure used for the DOSS 4.1 shown on Bendix assembly drawing 3153248 includes carbon steel weldment segments bolted together to support each pair of paired laminated nickel scrolls. The bolted segments form three structural columns which are terminated at each end by shock mount joints. The design intent of these joints is to simulate pin joints so that the columns shall not impose "fixed ended beam", bending moments on the remainder of the structural welds during periods when the transducer is subject to high driving forces. An additional function of the shock mounts is to prevent a shorted turn which would soak up energy of the magnetic field.

The shock mounts at top and bottom are restrained by structural steel members welded into triangles. The lower triangle is fastened to a base plate with large surface area so that the ground pressure is low as might be necessary when placing the transducer on a soft mud bottom.

The end segments of each column have an extension arm with a lug which engages the triangular end frames. The function of the lugs is to prevent rotation of the columns with resulting shear stresses on the neoprene which cushions the scrolls from the support arms of the welded segments.

Figure 42 is the transmitting current response from 500 to 1000 Hz with 15 amperes.

f_r = 750 cycles/sec T = 90.1 db R = 85 ohms Q_{mw} = 5 Eff. = 62%

The maximum source level was 113.6 db at 750 Hz with 15 amperes ac input current. Output is approximately 22 watts/pounds of active material.

(Figure 43 is a power curve at 750 Hz, Figure 44 is vertical patterns at resonance and at frequencies of approximate -3 db points, Figure 45 is an azimuth pattern at 750 Hz, Figure 46 is an azimuth pattern at 1468 Hz, Figure 47 is the high power impedance when driven unpolarized — measurements were made by filtering the voltage and current wave form and measuring the phase angle, Figure 48 is a power curve, when the transducer is operated without polarizing, and Figure 49 is the transmitting response when operating unpolarized with input currents of 2 to 15 amperes ac.)

DOSS 4.1 RESULTS

The DOSS 4.1 transducer scaled from the DOSS 3 close spaced array performed as expected and met all the design requirements. This verifies the feasibility of building models to establish the design and scaling lower frequency transducers from the model with predictable performance.

Section 5

DESIGN OF THE LOW FREQUENCY TRANSDUCER

Based on the results of the program previously described, dimensions for the design of the full sized transducer have been established and is illustrated on Bendix Drawing 3162100.

Some variations in the structure have been incorporated to improve transverse structural stiffness necessary for a transducer weighing in the order of five tons. These variations include increasing the number of structural support columns from three to six and the addition of three diagonal struts.

The anticipated weight and cable tension loads of the electrical winding also has resulted in a revision to the design of winding support rings.

Cost of a scaled up fiberglass ring to support the cable loads would be very substantial. On the models, the rings were integral layed up rings with solid cross-sections. This was necessary to obtain an adequate section modulus to react the bending loads. Their cost was high relative to other components needed to build the transducer. Therefore, for the low frequency transducer, a segmented, bolted together ring has been proposed. Each segment is isolated electrically from the remainder of the ring to eliminate shorted ring effects.

The proposed scroll dimensions are scaled from the DOSS 4.1 and DOSS 3 to achieve the frequency requirements of specification 689A-0399. Because of the classified nature of the referenced document the scroll dimensions, which in conjunction with this report would yield the frequency of the transducer, are classified. This classified drawing is Bendix Drawing 3162088.

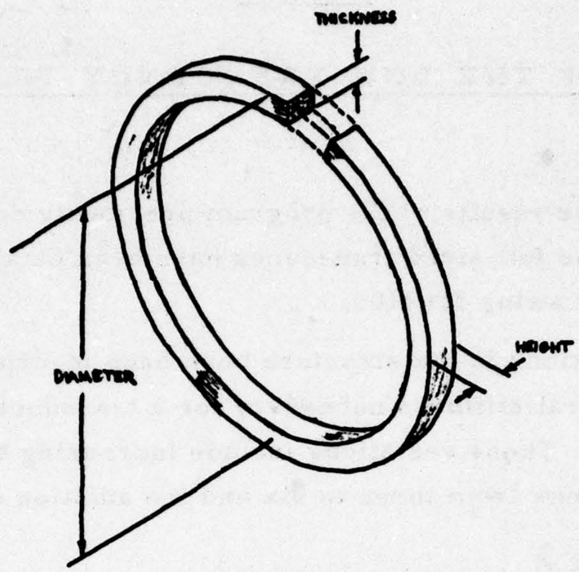

Figure 1. Scroll Dimensions

Figure 2. DOSS 1-8 Transducer on Test Fixture

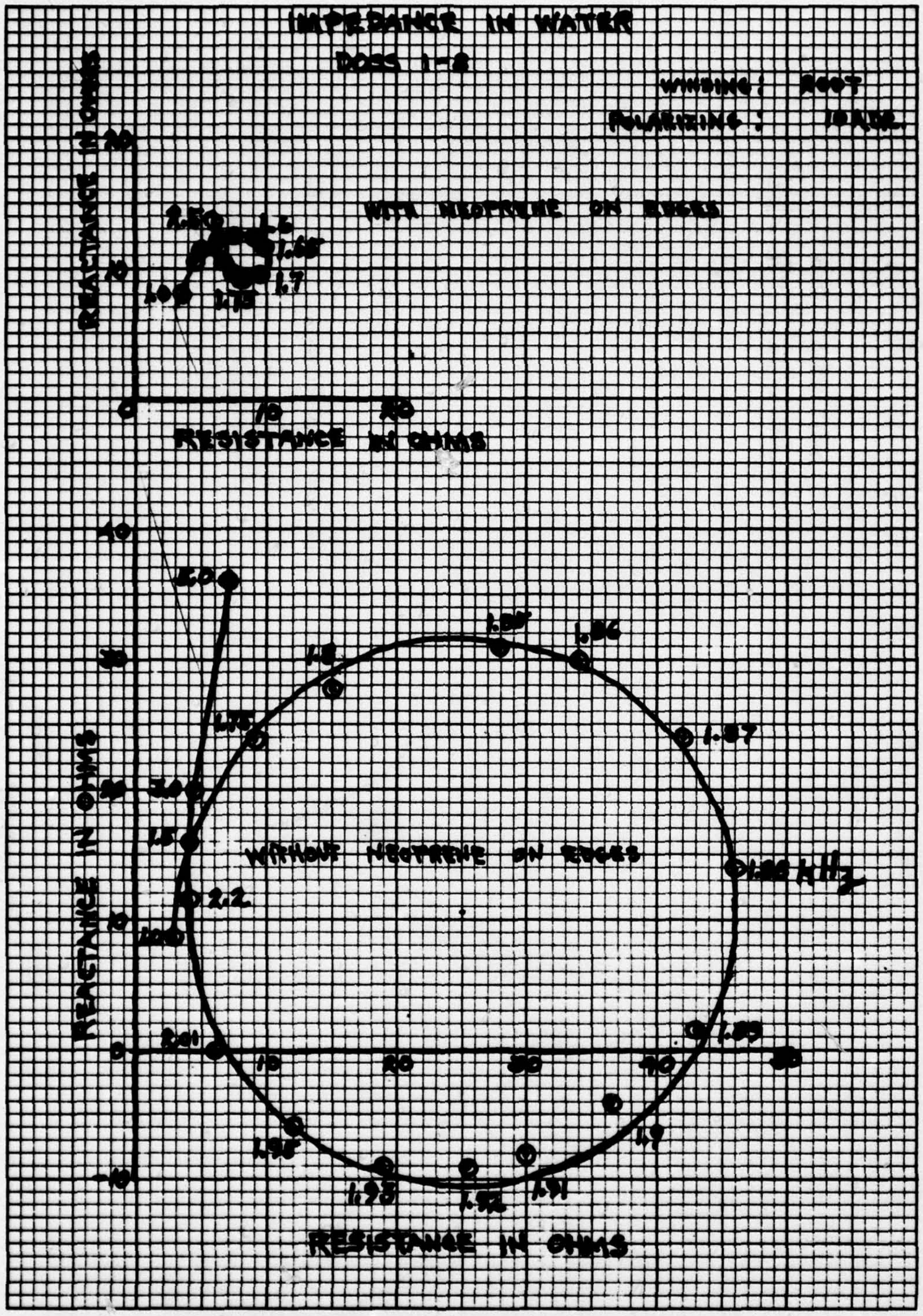

Figure 3. Impedance Circles, With and Without Neoprene on Edges

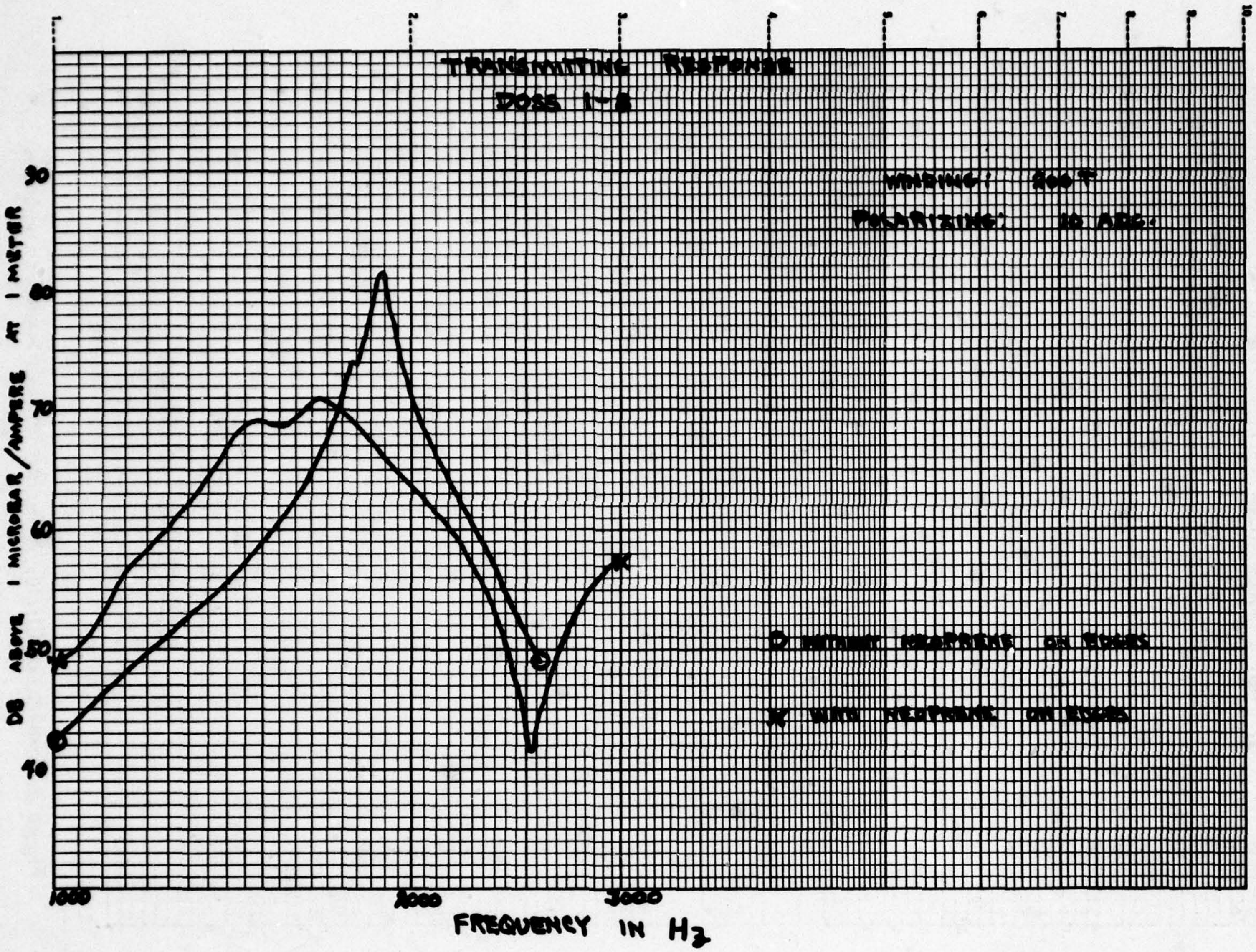

Figure 4. Transmitting Response, With and Without Neoprene on Edges

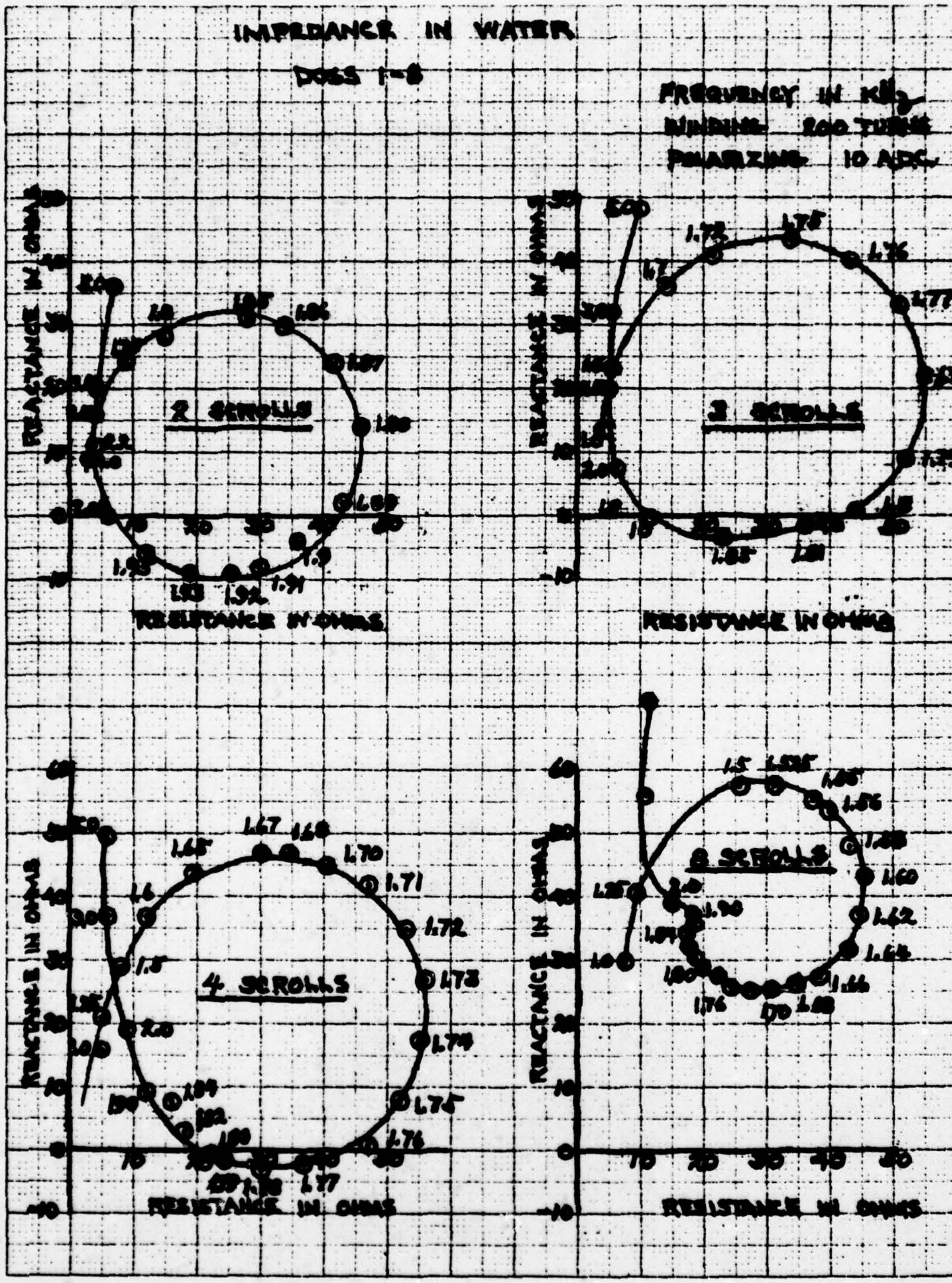

Figure 5. Impedance Circles, 2, 3, 4 and 8 Scrolls

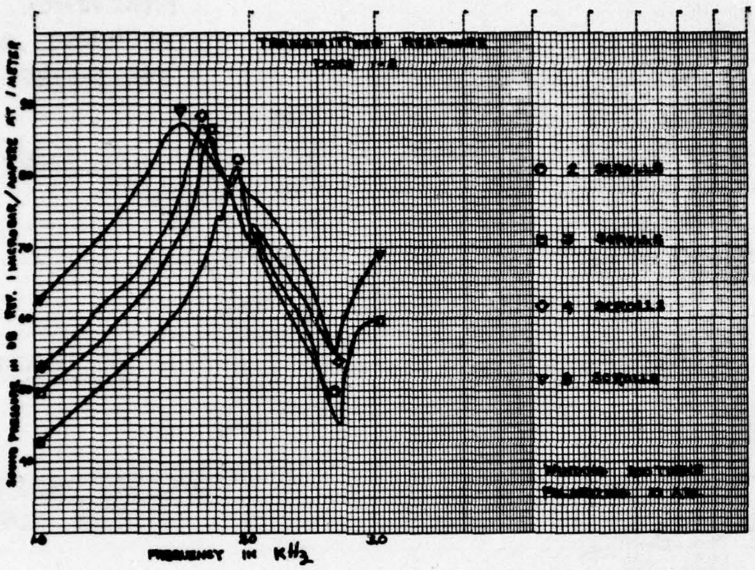

Figure 6. Transmitting Response, 2,3, 4 and 8 Scrolls

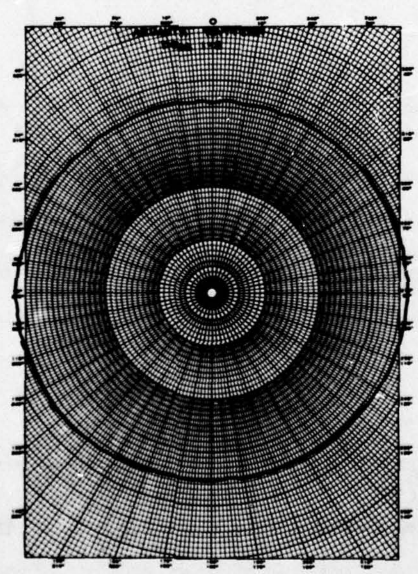

Figure 7. Typical Azimuth Pattern, at Resonance

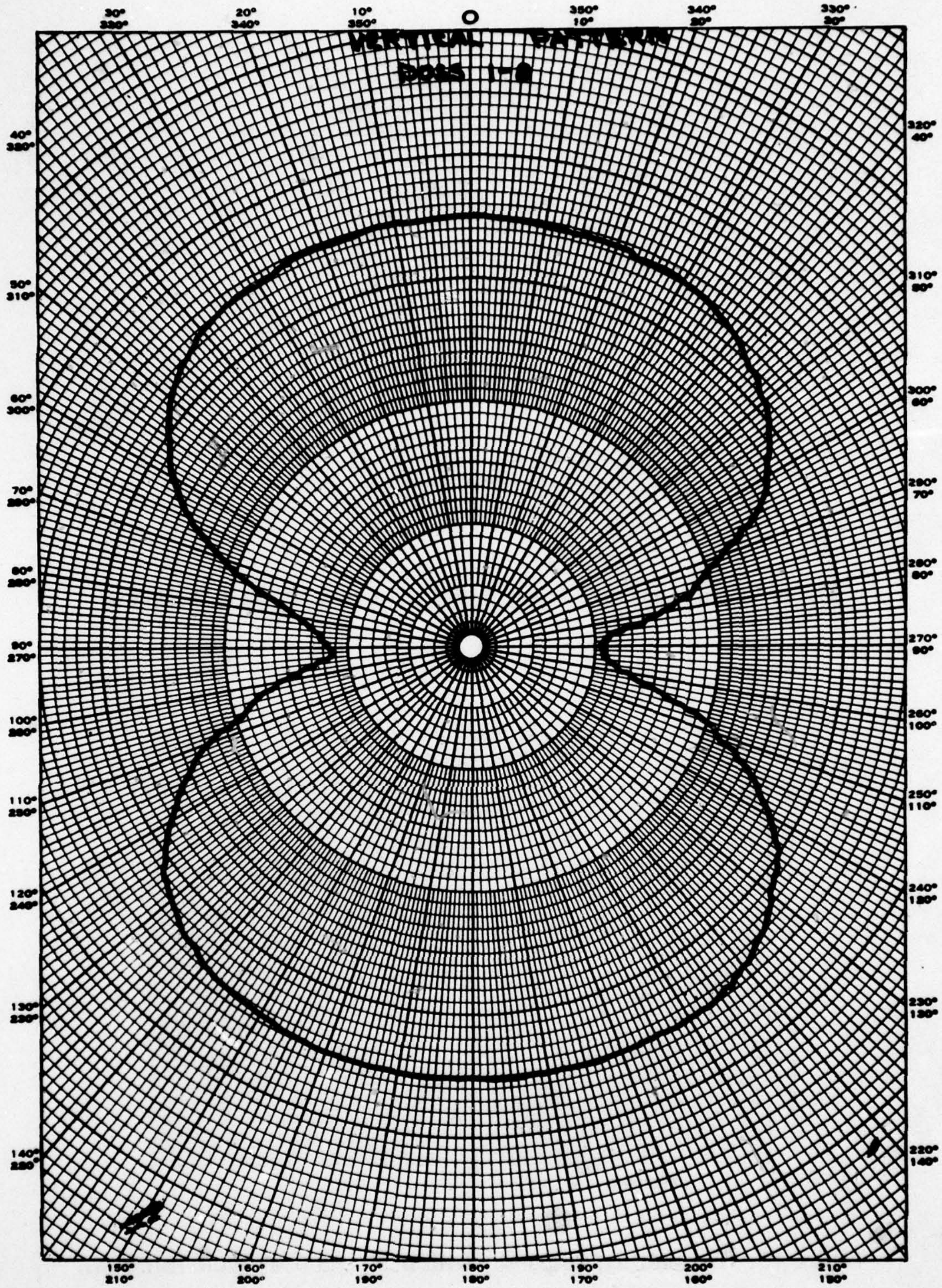

Figure 8. Typical Vertical Pattern, at Resonance

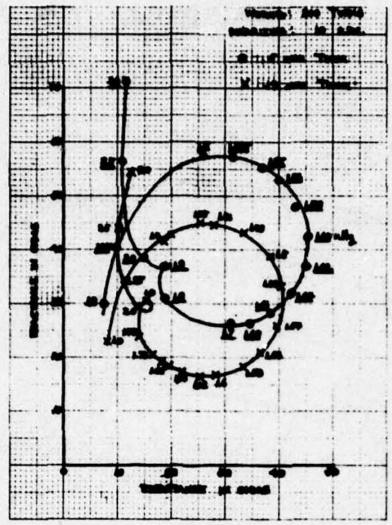

Figure 9. Impedance Circles, with 0.5" and 0.4" Wall Thickness

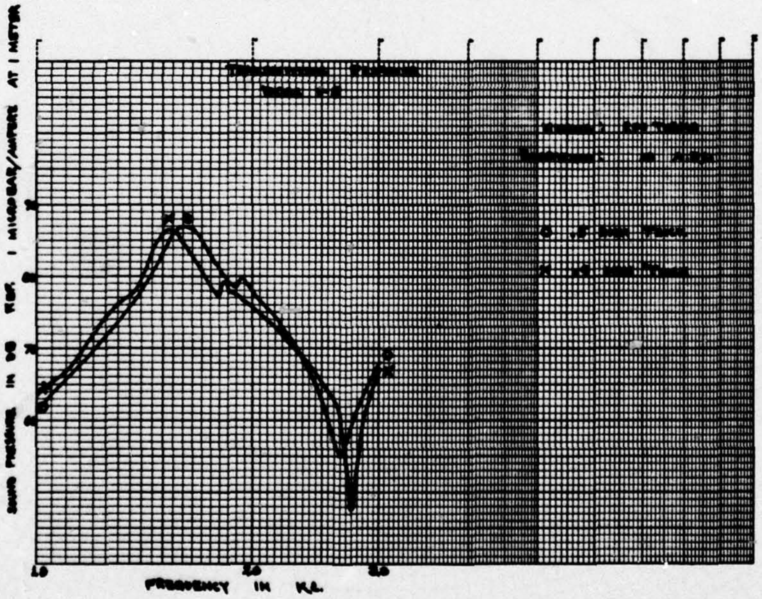

Figure 10. Transmitting Response, with 0.5" and 0.4" Wall Thickness

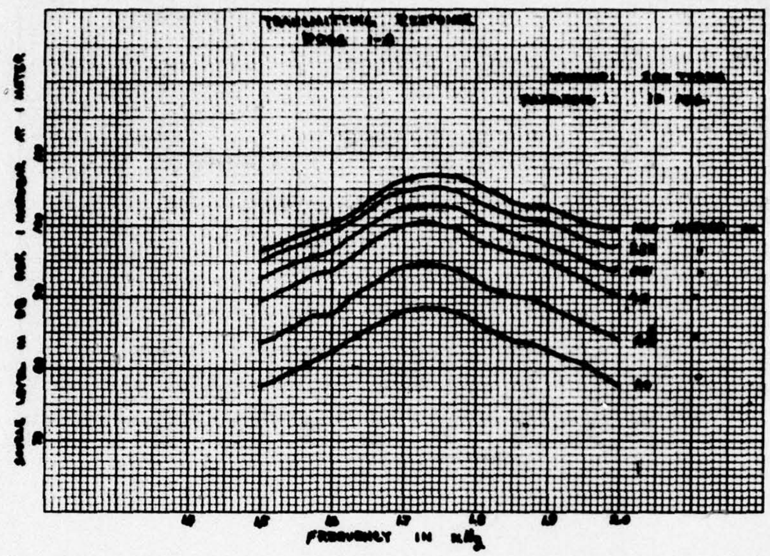

Figure 11. Transmitting Response, with 10 Ampere D.C. Polarizing

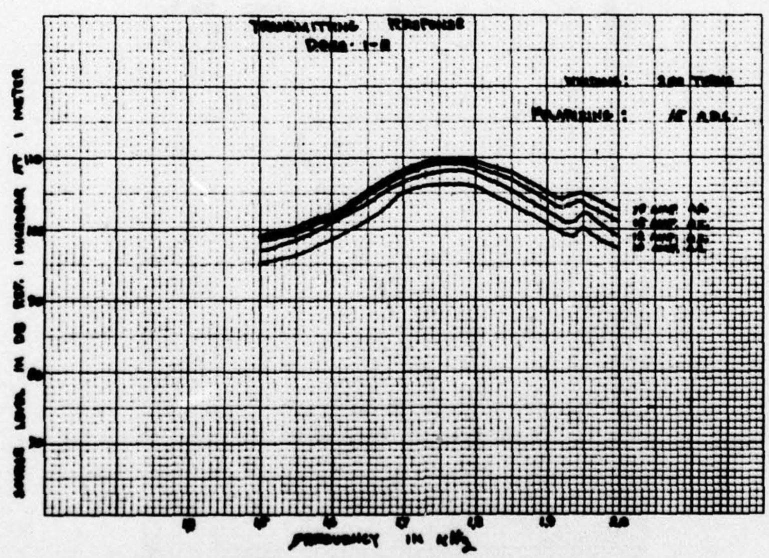

Figure 12. Transmitting Response, with 15 Ampere D.C. Polarizing

Figure 13. Transmitting Response, Unpolarized

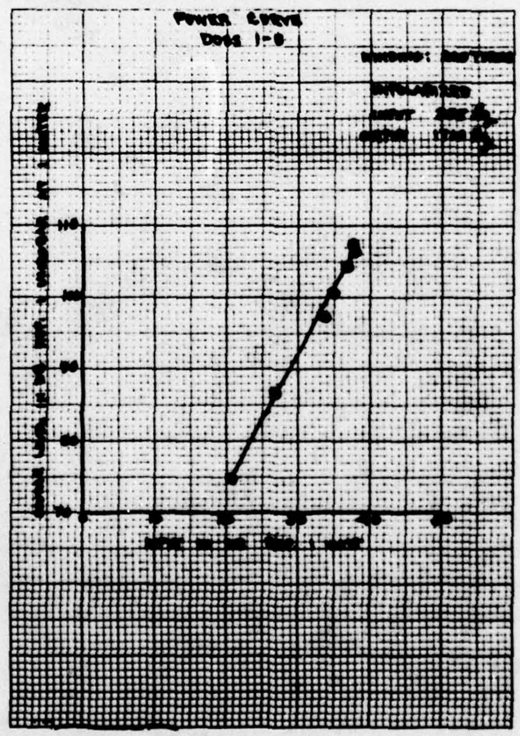

Figure 14. Power Curve, Unpolarized

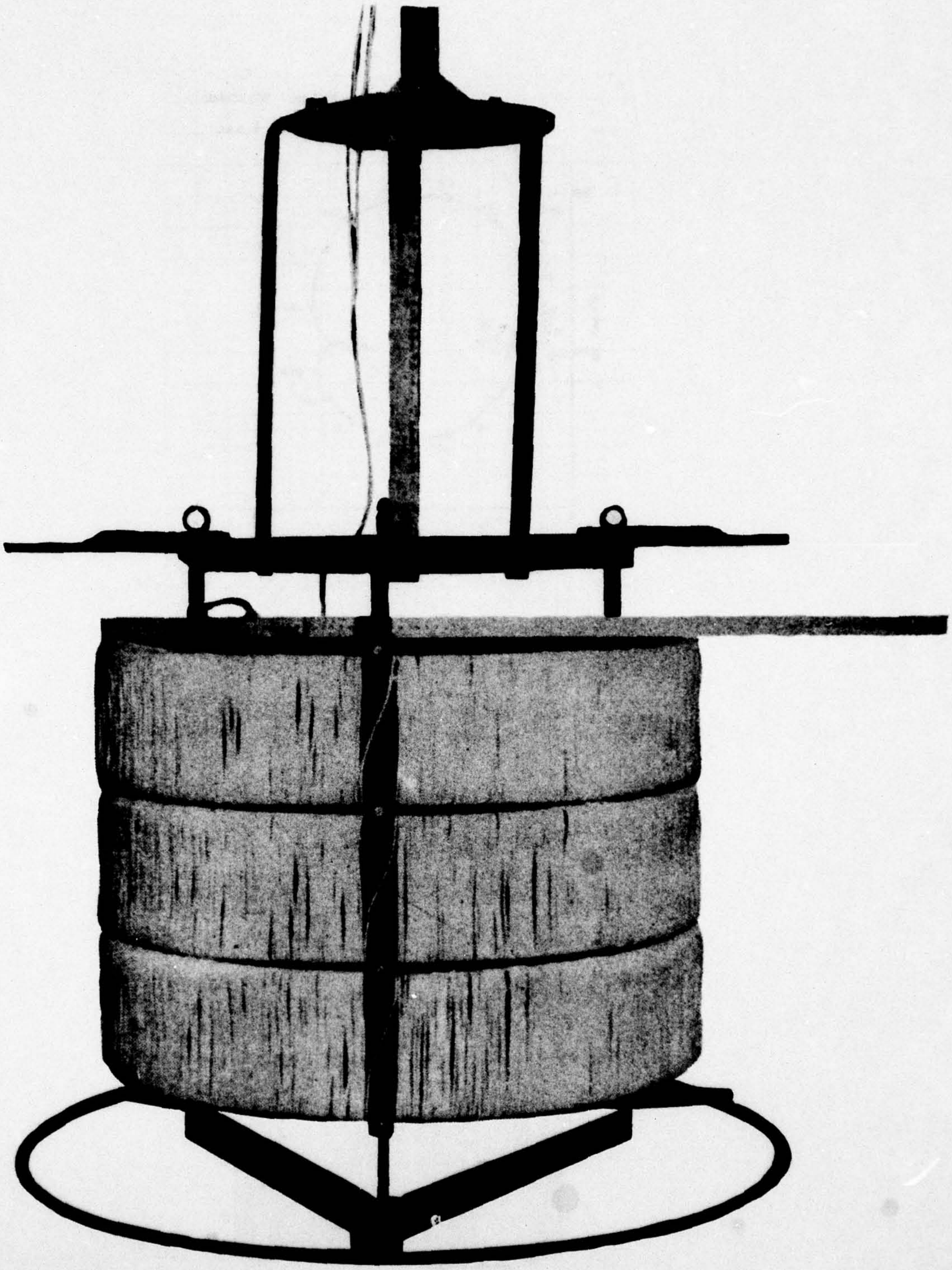

Figure 15. DOSS 2 Transducer

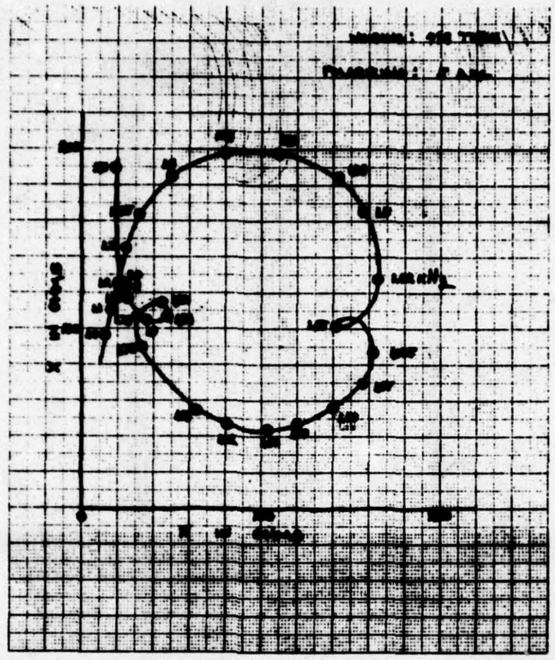

Figure 16. Impedance Circle

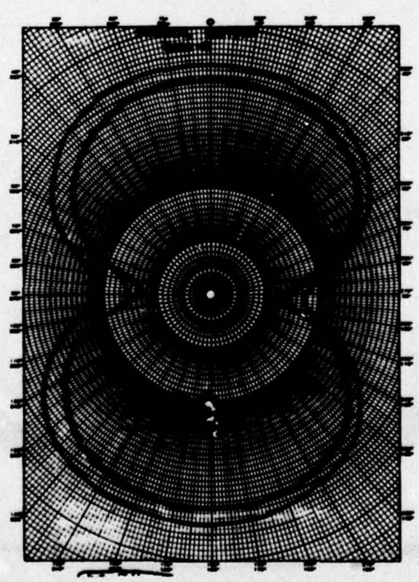

Figure 17. Vertical Patterns, at Resonance and Near Resonance

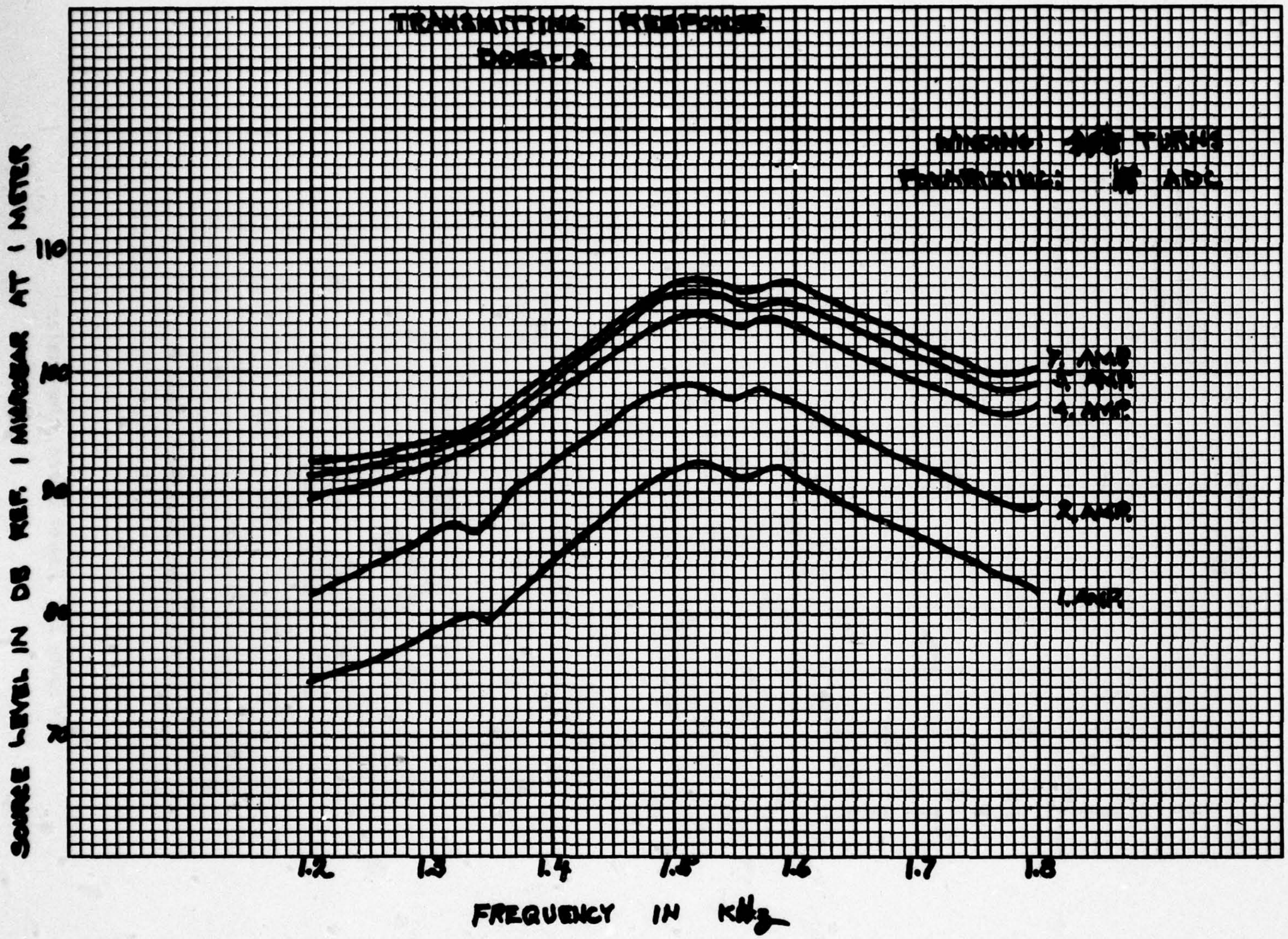

Figure 18. Transmitting Response, Polarized

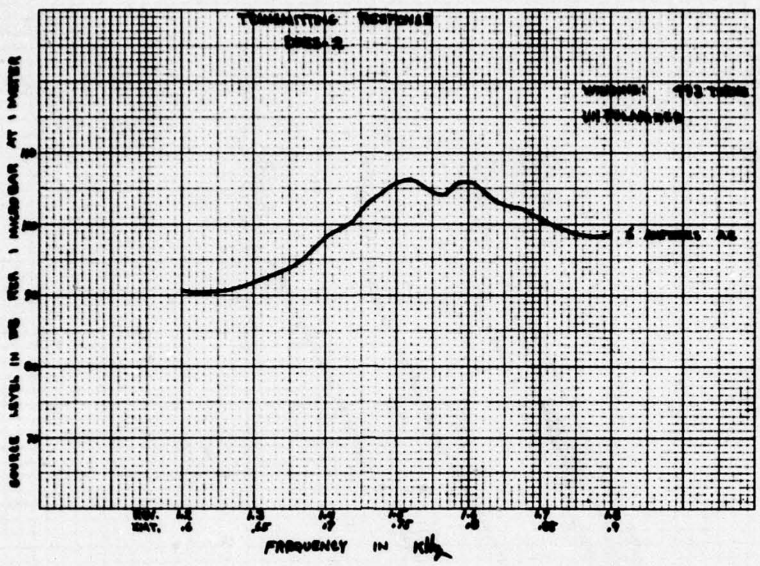

Figure 19. Transmitting Response, Unpolarized

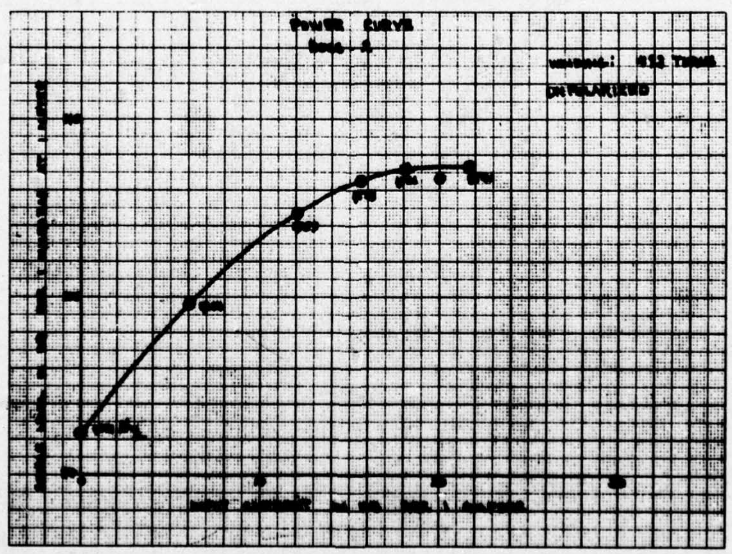

Figure 20. Power Curve, Unpolarized

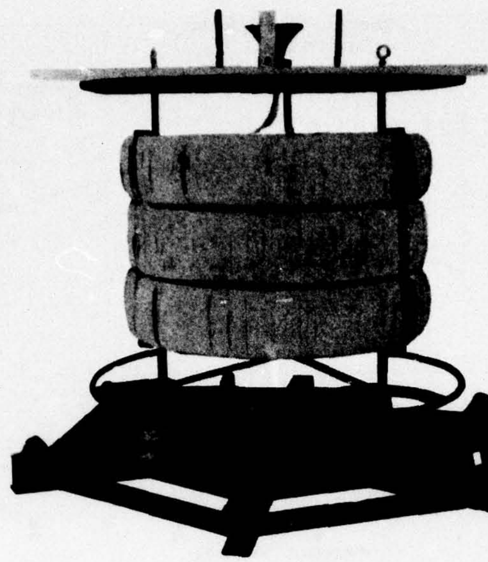

Figure 21. DOSS 3 Transducer with Mounting Base

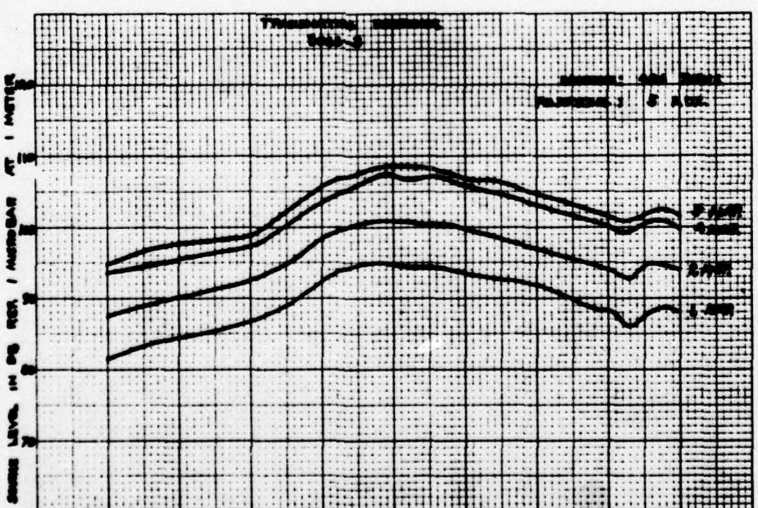

Figure 22. Transmitting Response, Polarized - 0.42 Wall Thickness

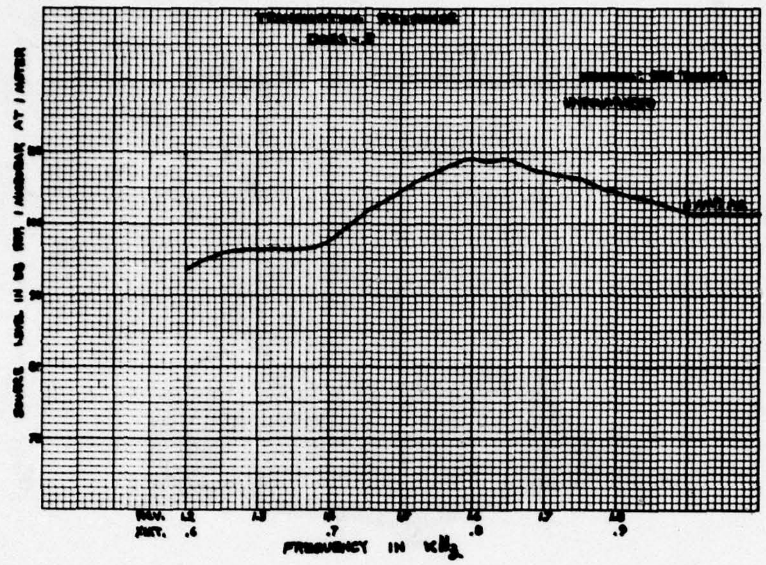

Figure 23. Transmitting Response, Unpolarized 0.42 Wall Thickness

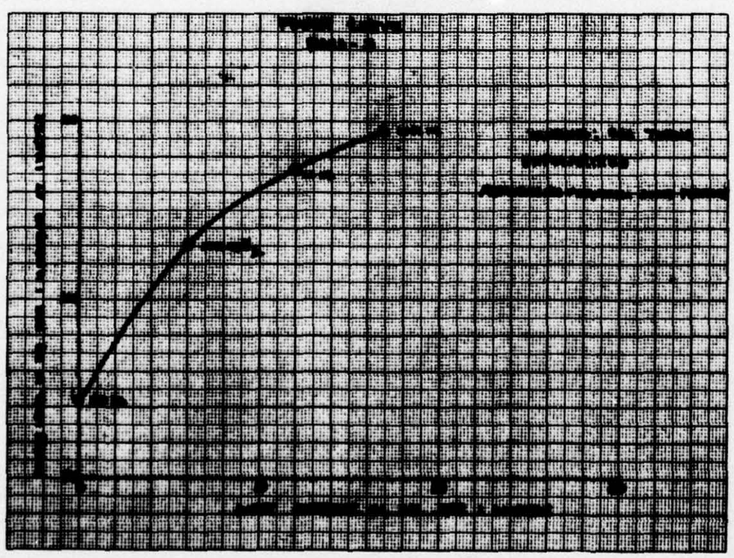

Figure 24. Power Curve, Unpolarized

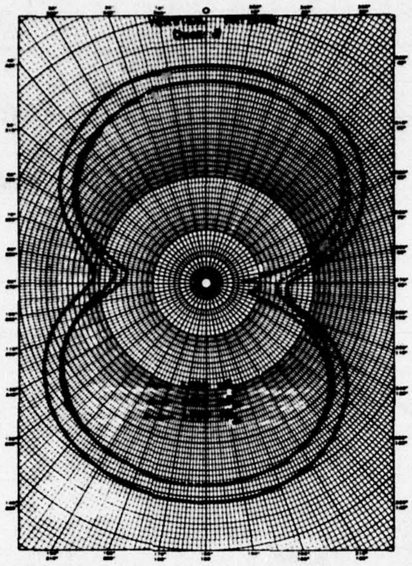

Figure 25. Vertical Patterns with Mounting Base

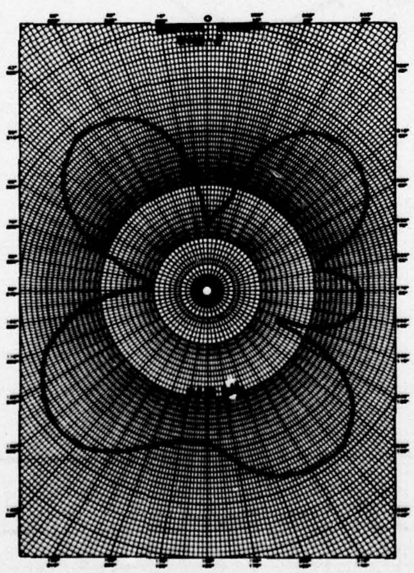

Figure 26. Vertical Pattern at 2610 Cycles/Sec

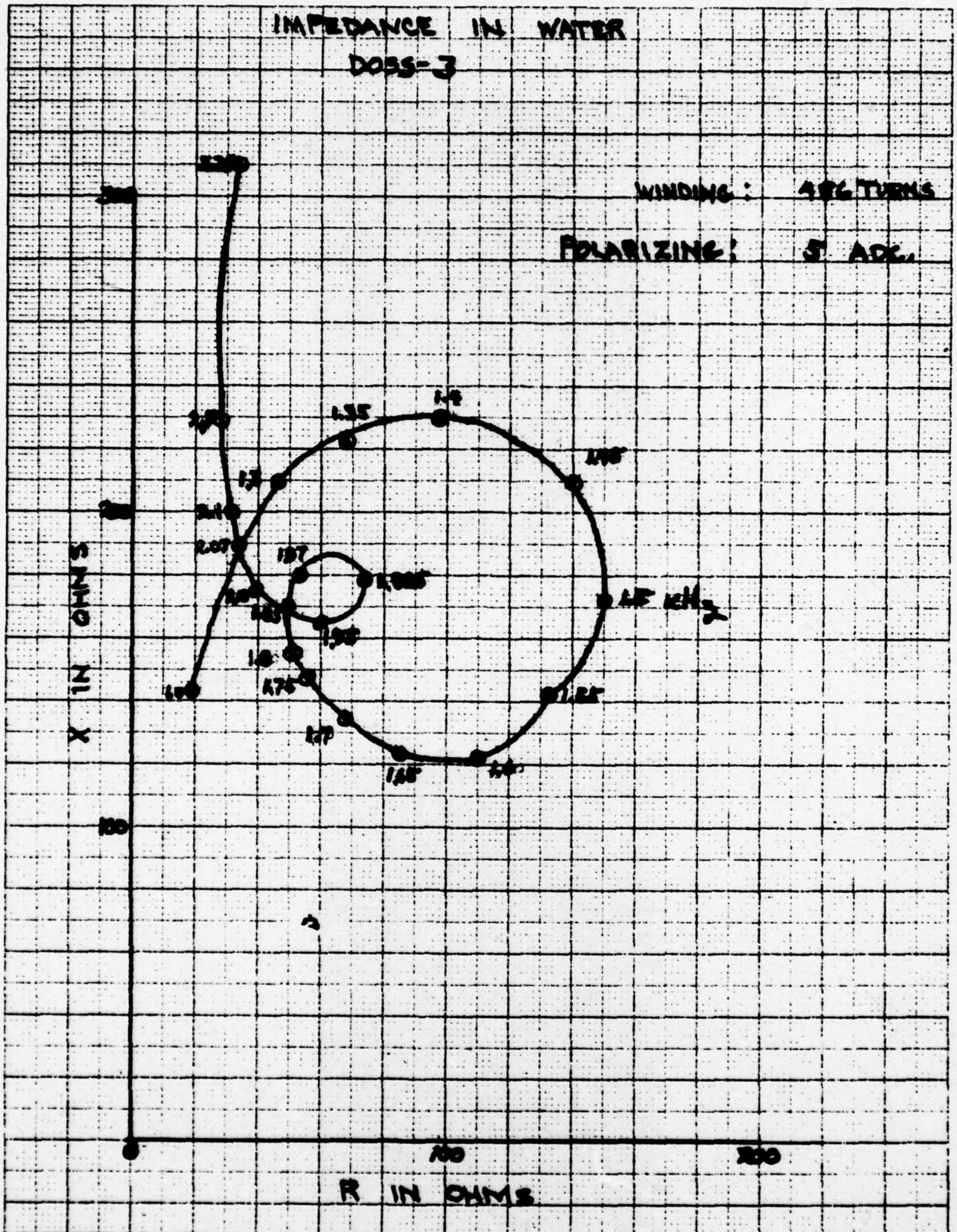

Figure 27. Impedance Circle - 0.32 Wall Thickness

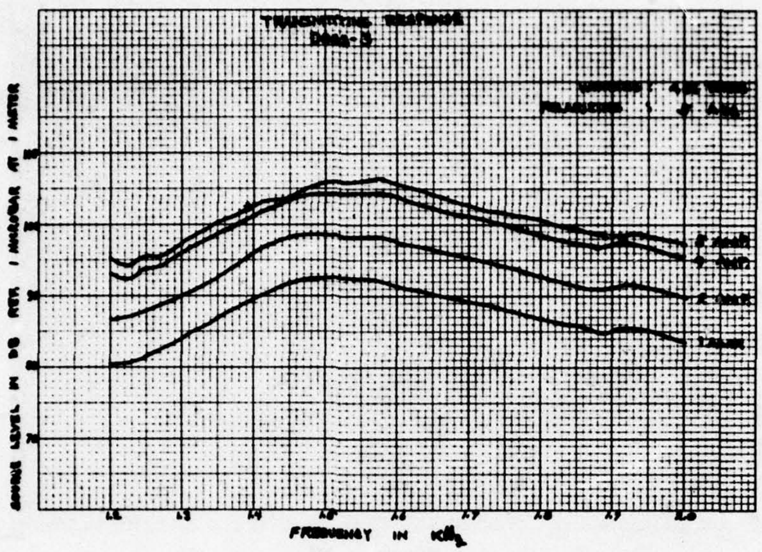

Figure 28. Transmitting Response Polarized - 0.32 Wall Thickness

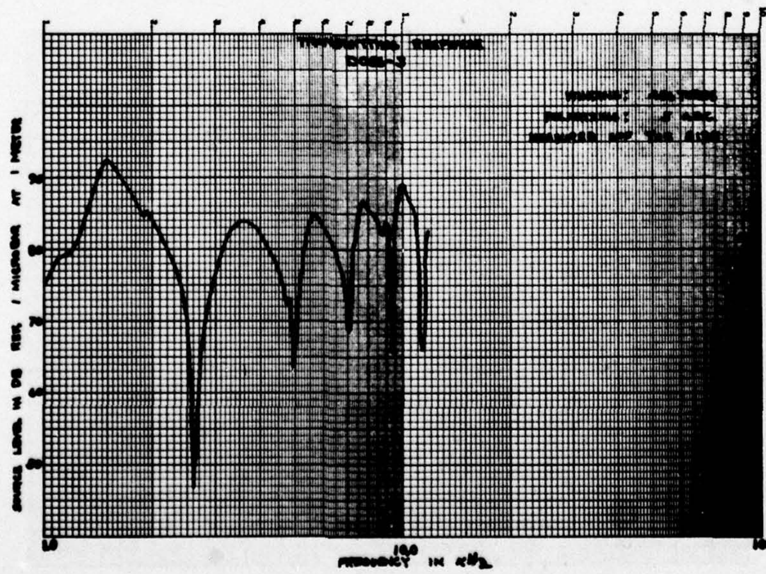

Figure 29. Transmitting Response 1 to 10 kc Measured Off the Side

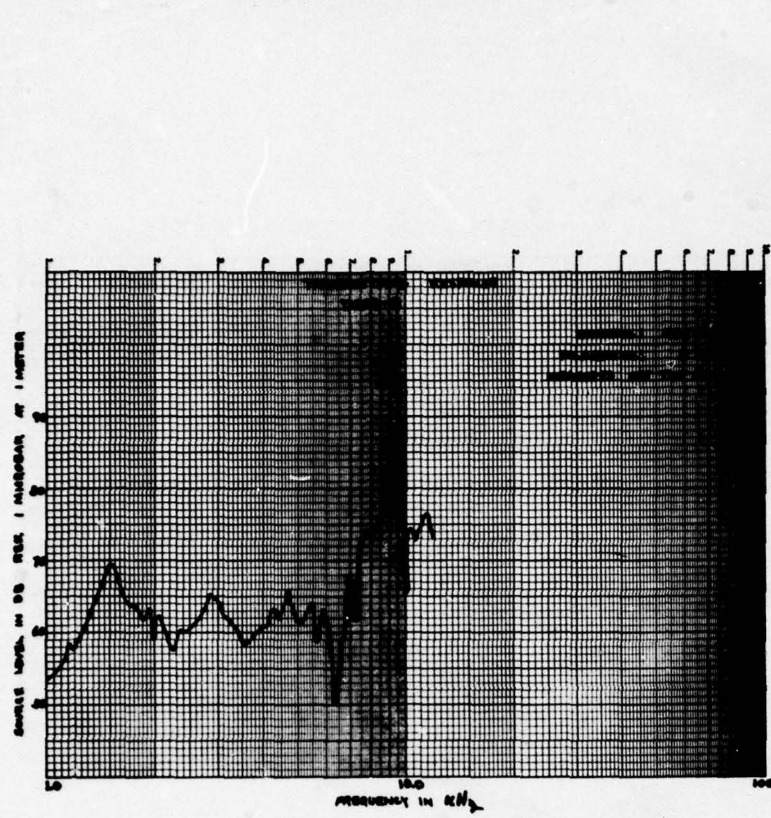

Figure 30. Transmitting Response 1 to 10 kc Measured Off the End

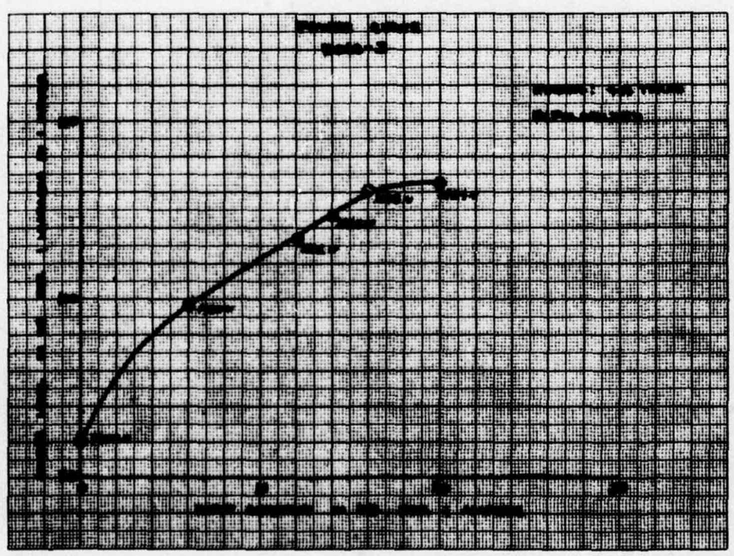

Figure 31. Power Curve Unpolarized - 0.32 Wall Thickness

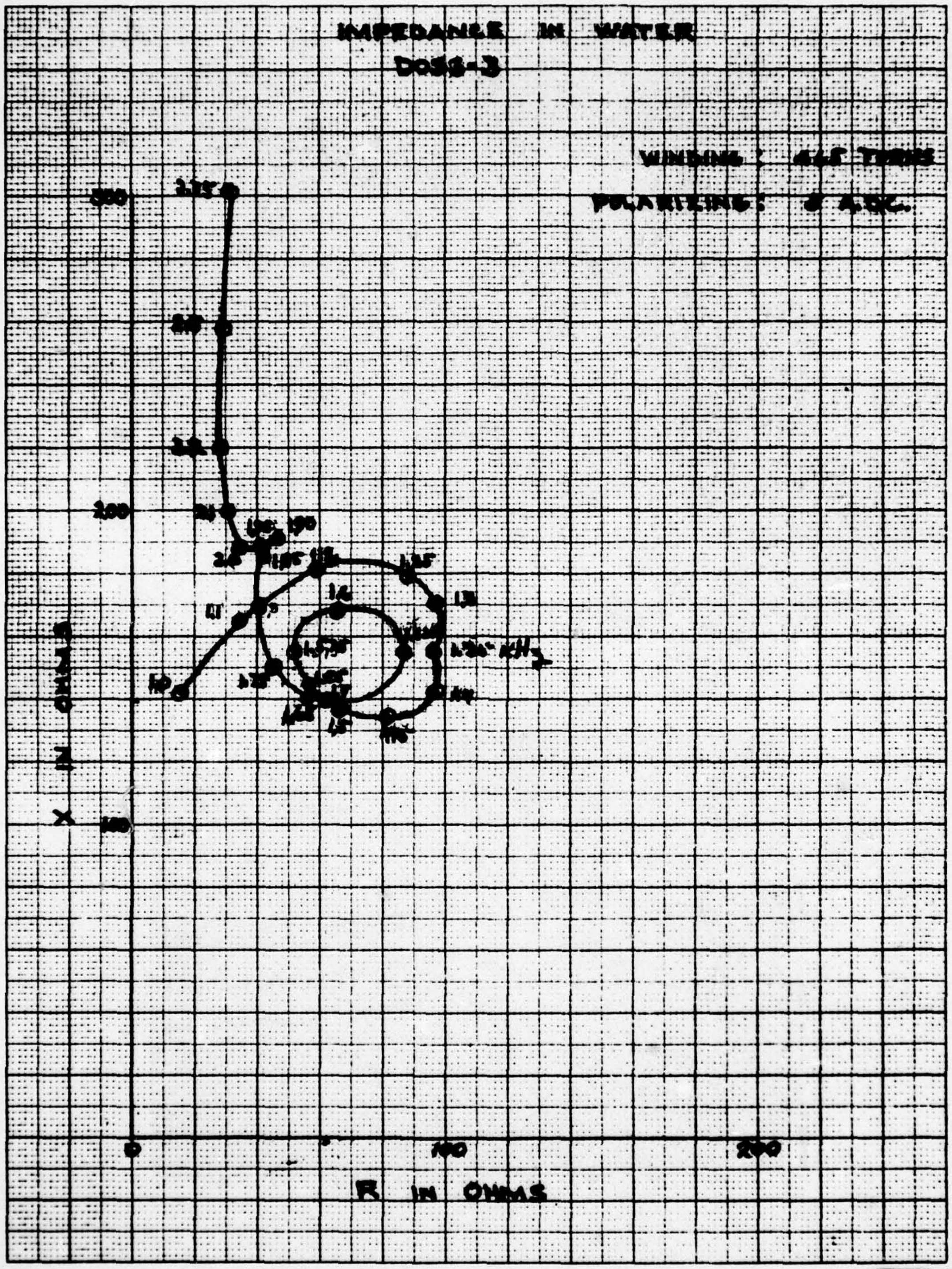

Figure 32. Impedance Circle - Close Spaced with Common Winding

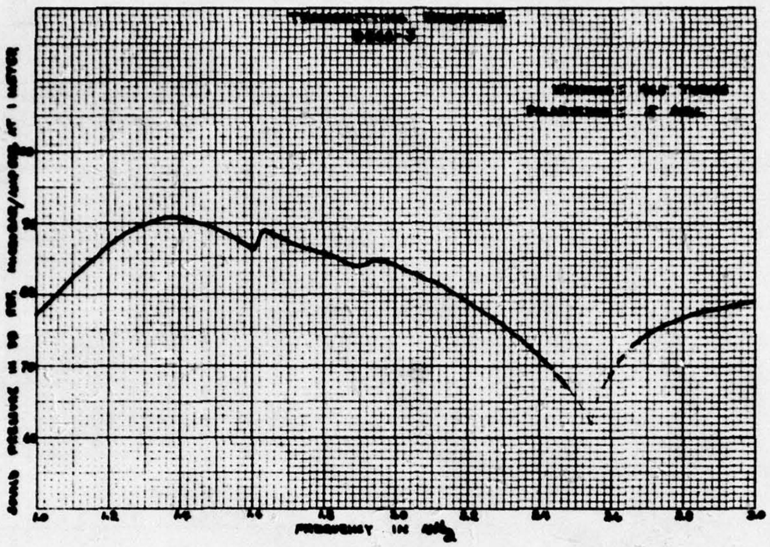

Figure 33. Transmitting Response

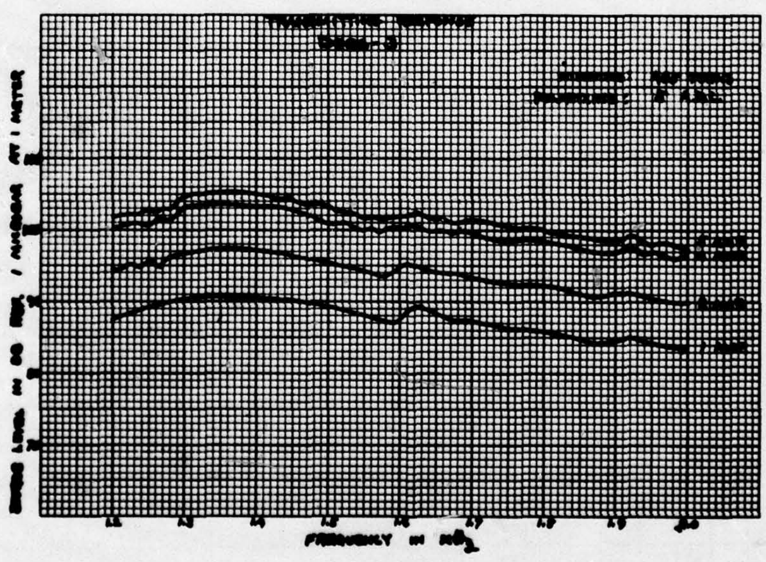

Figure 34. Transmitting Response

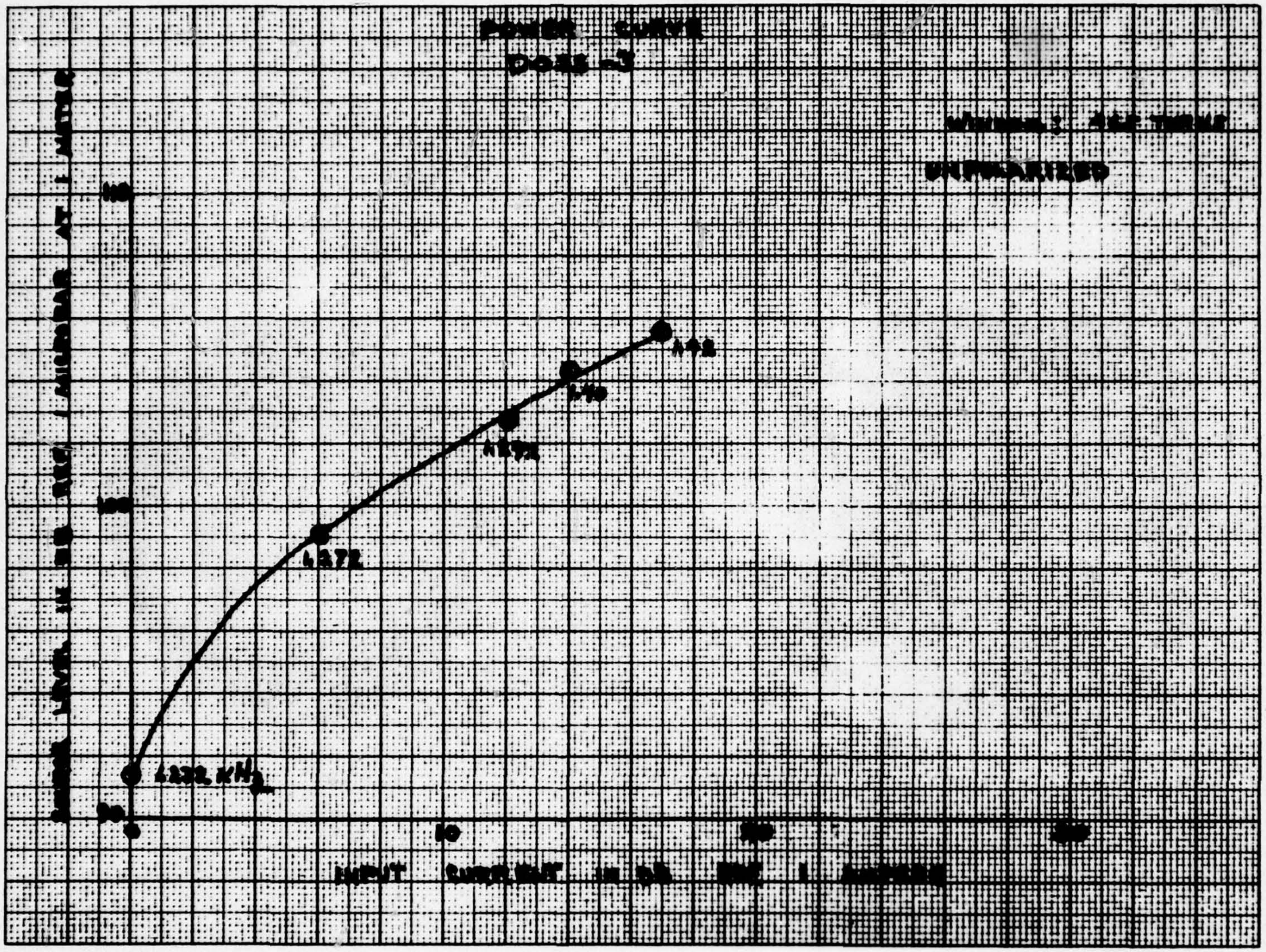

Figure 35. Power Curve, Unpolarized

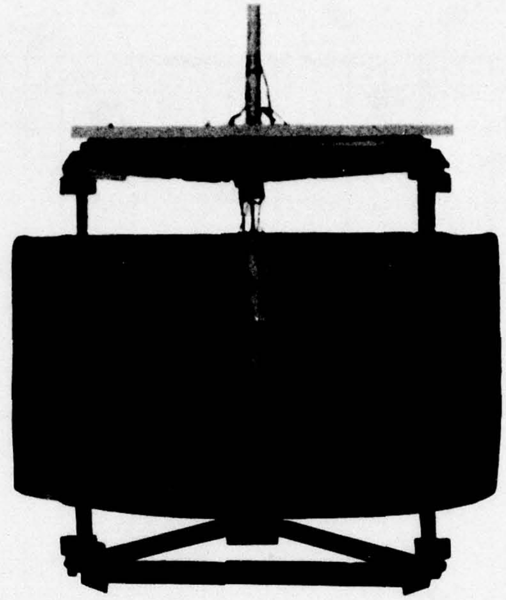

Figure 36. DOSS 4-1 Transducer

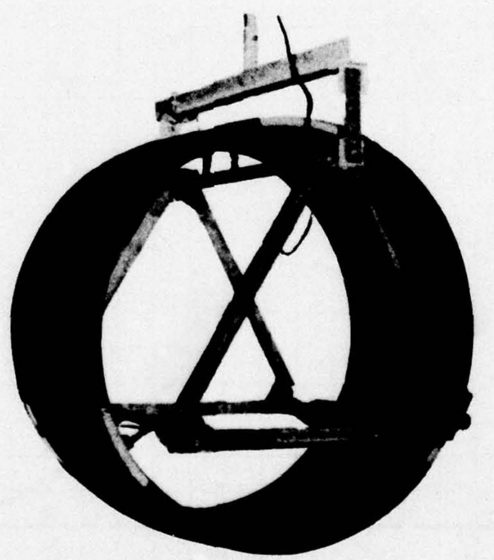

Figure 37. DOSS 4-1 Transducer

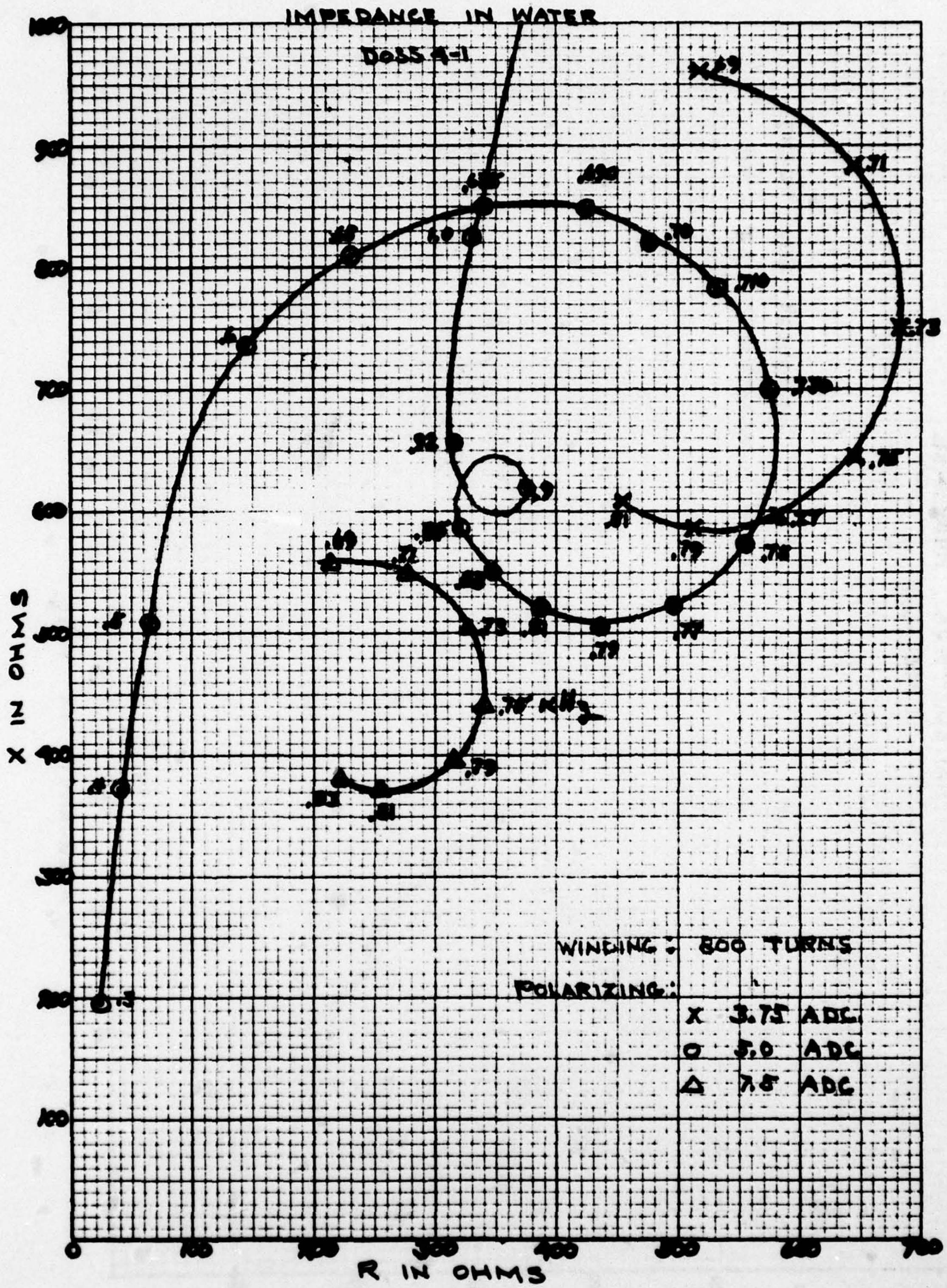

Figure 38. Impedance Circles, in Water

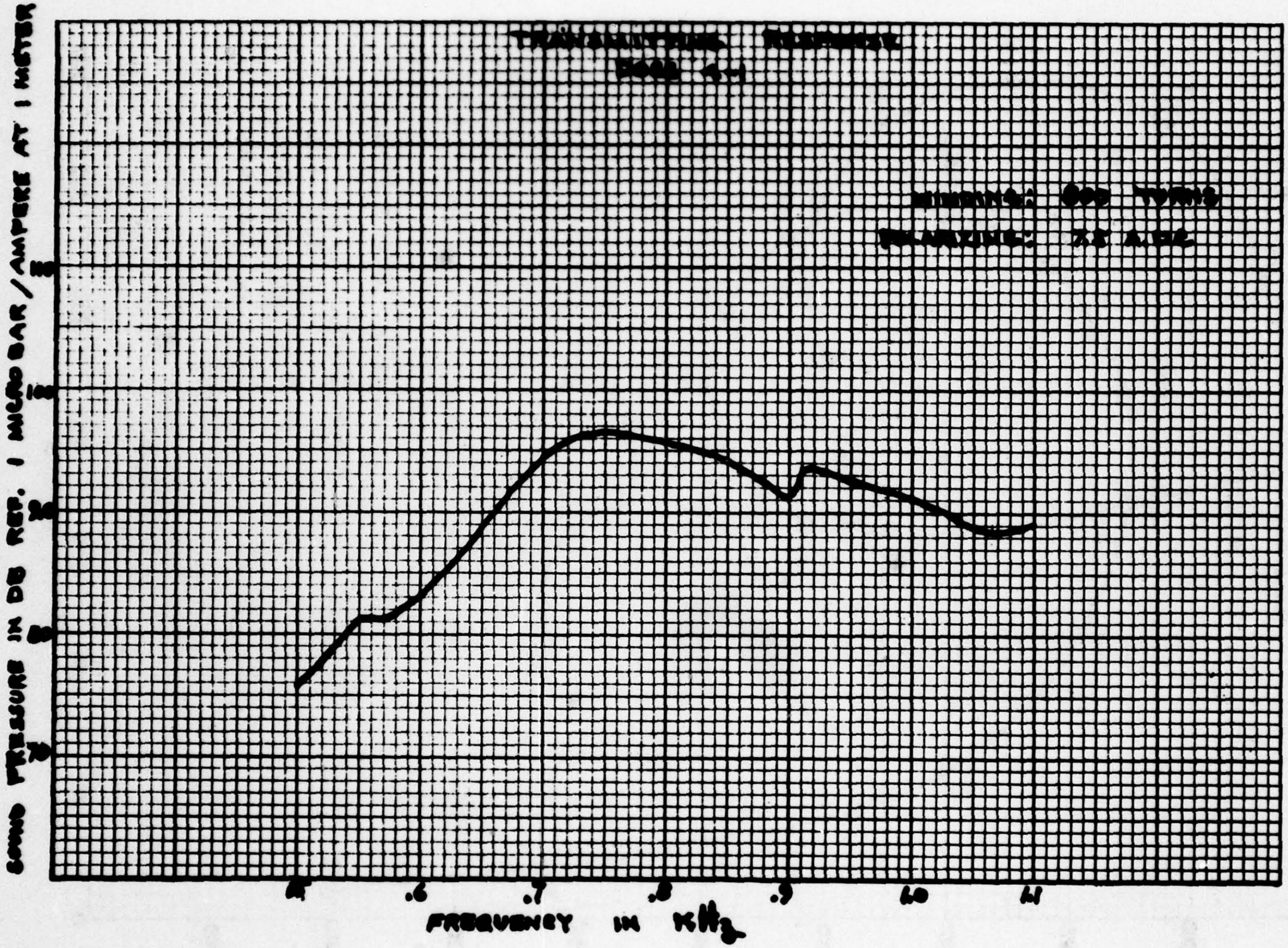

Figure 39. Transmitting Response

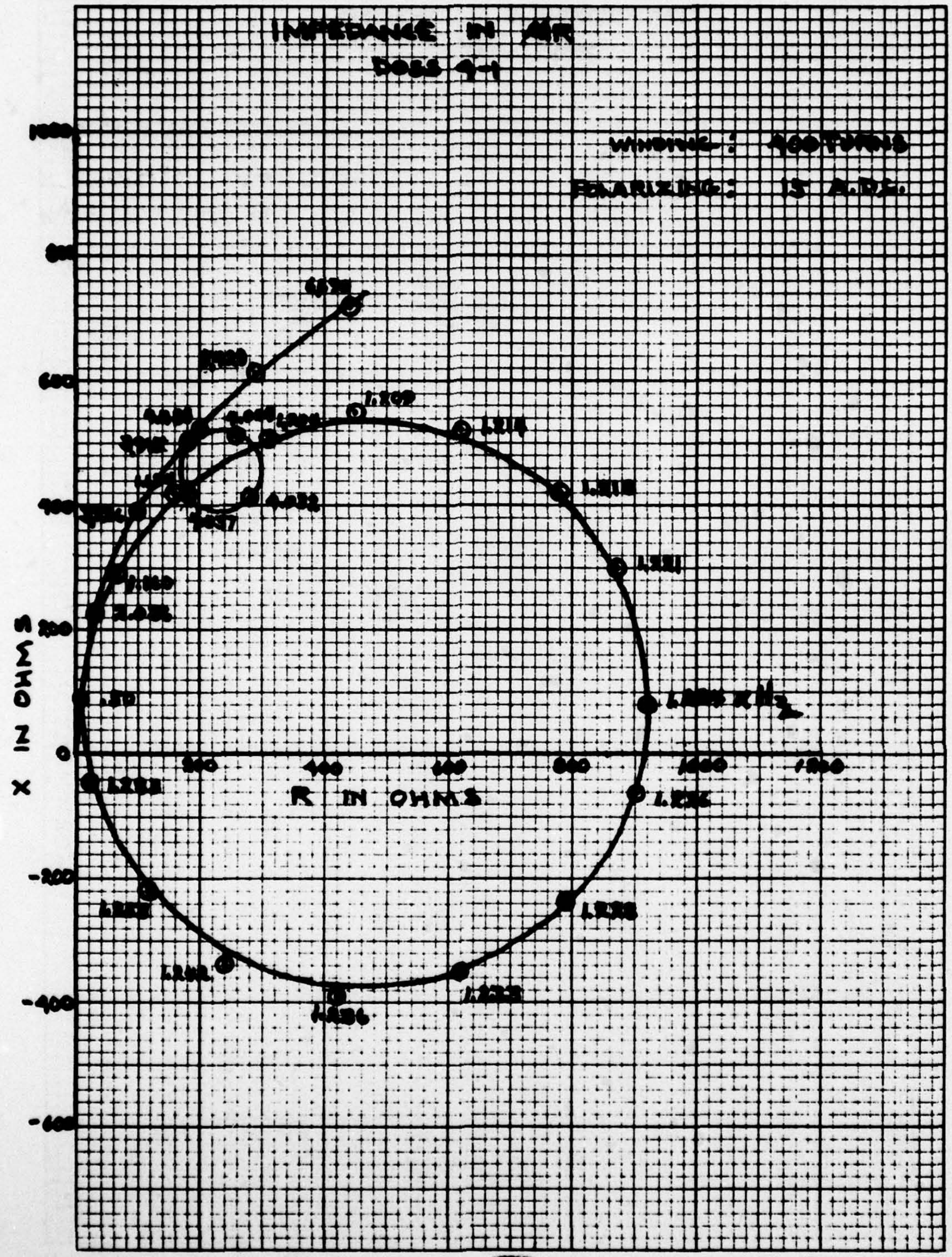

Figure 40. Impedance Circle, in Air

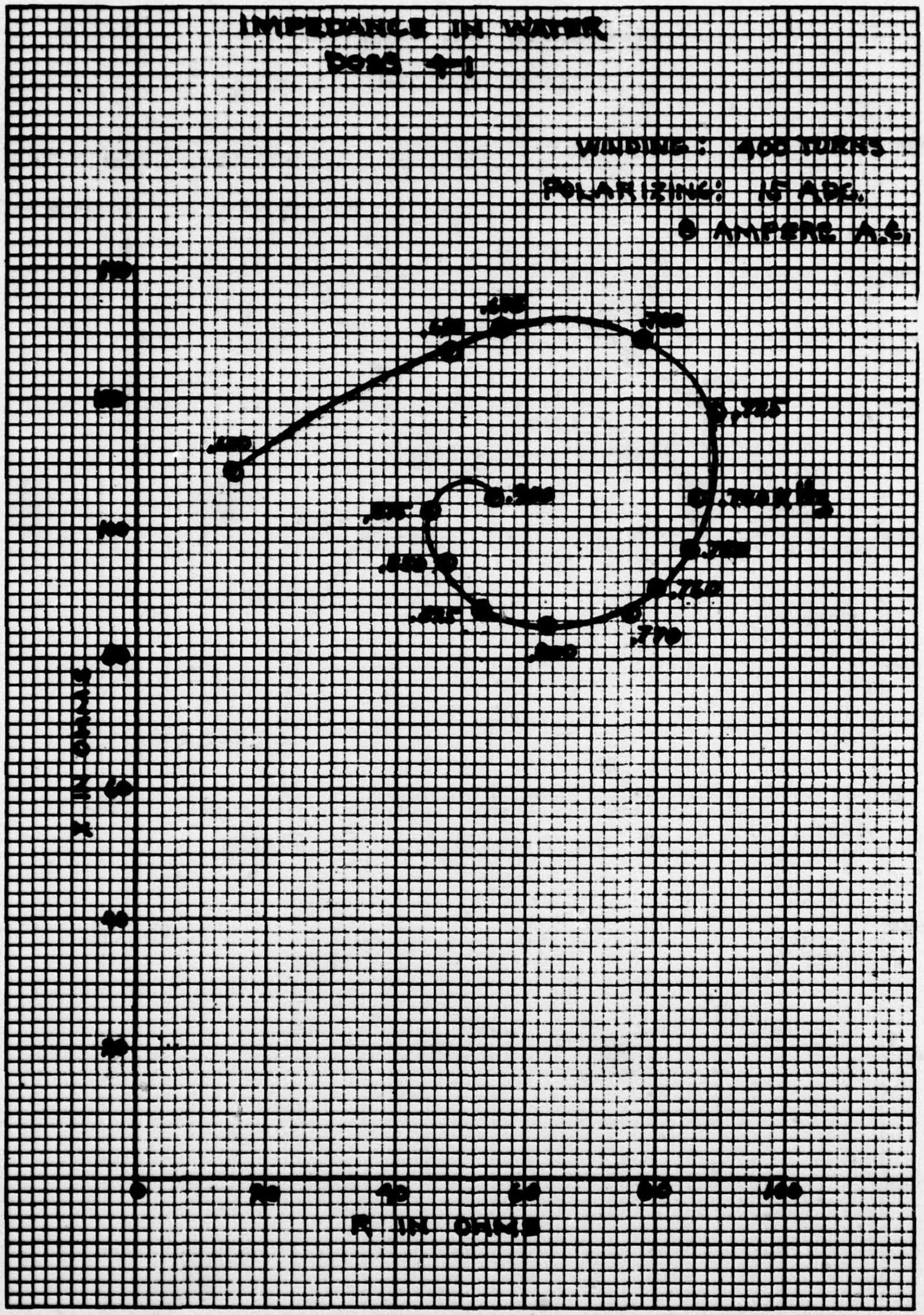

Figure 41. Impedance Circle, in Water

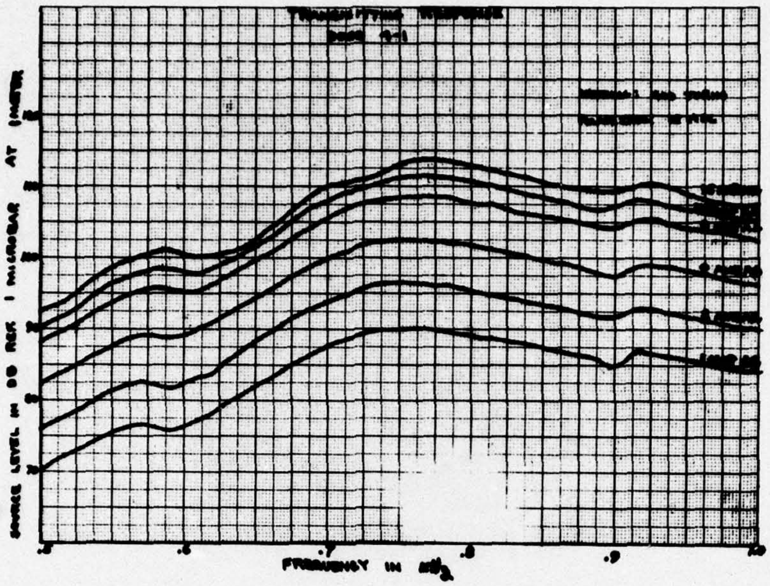

Figure 42. Transmitting Response, Polarized

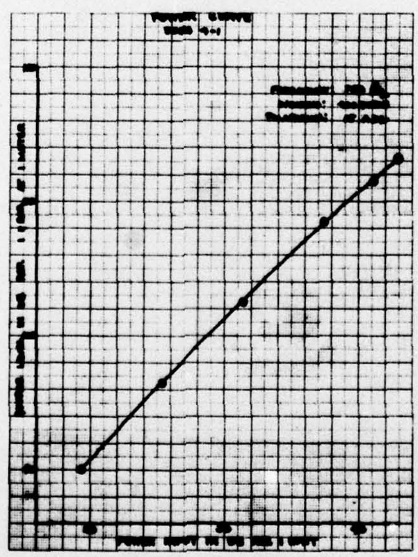

Figure 43. Power Curve, Polarized

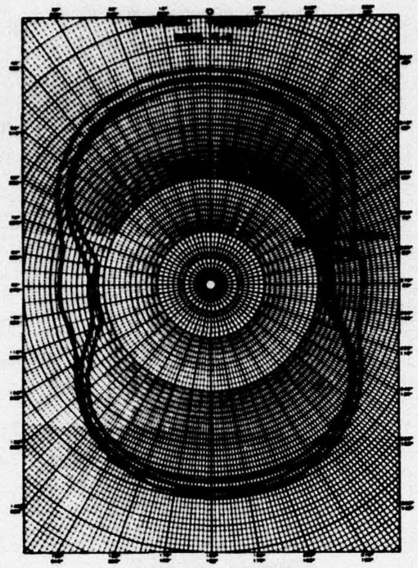

Figure 44. Vertical Patterns, at Resonance and Near Resonance

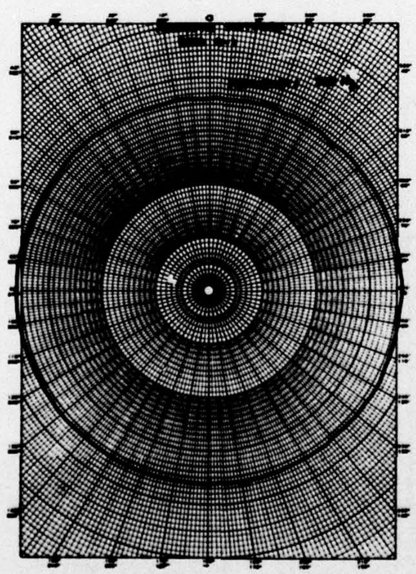

Figure 45. Azimuth Pattern, at Resonance and Near Resonance

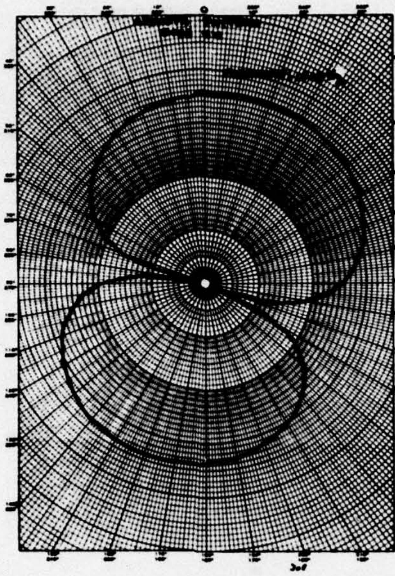

Figure 46. Azimuth Pattern, 1468 Cycles/Sec

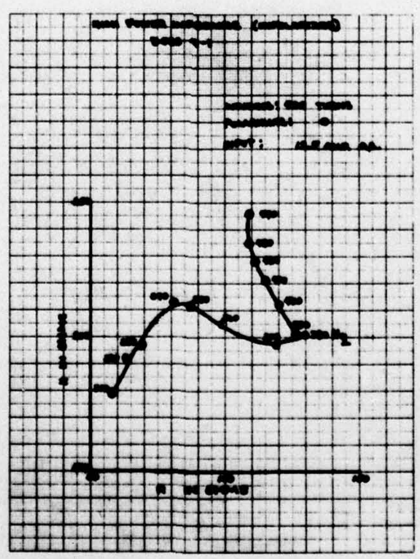

Figure 47. High Power Impedance, Unpolarized

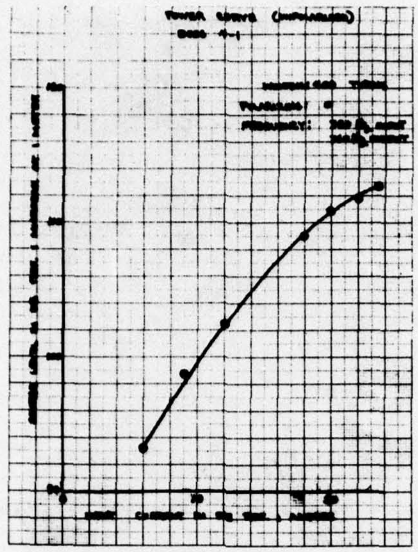

Figure 48. Power Curve, Unpolarized

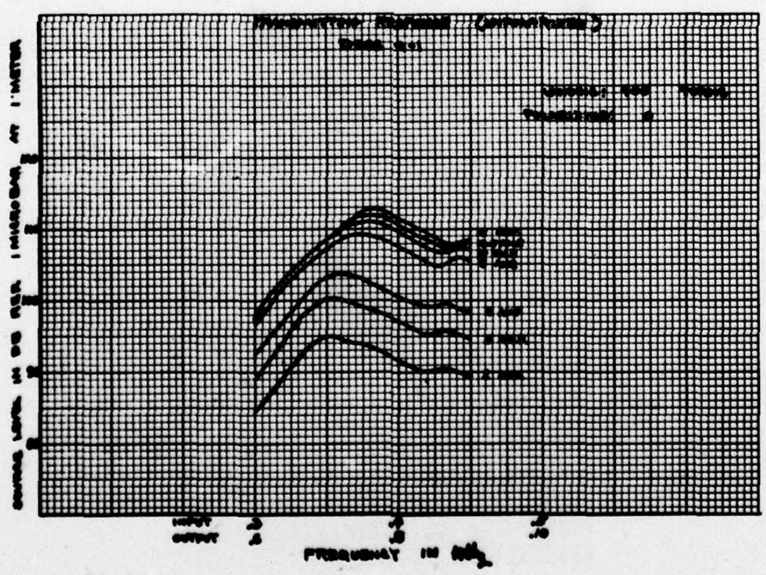

Figure 49. Transmitting Response, Unpolarized

APPENDIX 1

APPENDIX 1

Design of the components of a magnetostrictive scroll transducer.

1. These transducers are essentially thin-walled right circular cylinders where the useful radiation pattern is from the exterior cylindrical surface only. The radiation pattern is that of a line source. The beam width at the -6 db points is given by the equation:

$$L \sin a = 0.6 \lambda \tag{1}$$

Where L is the total length of the line, 2a is the beam width and λ is the wave length of sound in the medium at the frequency being used.

Under the same conditions, the directivity gain, D, in db is given by

$$D = 10 \log \frac{2L}{\lambda} \tag{2}$$

These equations become more accurate as the cylinder increases in length.

The transducers for this contract consist of a stacked assembly of thin-walled rings to form a cylinder of the desired length. The resonant frequency of the fundamental radial mode of the cylinder is given by

$$A = \frac{C_m}{2\pi f_r} \tag{3}$$

Where "A" is the mean radius of the cylinder, f_r is the resonant frequency in cycles per second and C_m is the velocity of sound in the cylinder wall.

If this array were a long cylinder, with its interior not in contact with the medium, equation (3) would hold when the transducer is immersed. Also under these conditions, the mechanical Q_m of the transducer would be:

$$Q_m = \frac{b\, \rho_m\, c_m}{A\, \rho c} \tag{4}$$

where b is the wall thickness, ρ_m and c_m are the density and velocity of sound respectively in the cylinder wall and ρ and c are like properties of the medium.

For free-flooded scroll assemblies equations (3) and (4) must be modified. There is no existing theory that satisfactorily replaces these design equations. However, from the experimental results taken from models a useful relationship was developed relating C_m of equations (3) and (4) to the radiation impedance.

For example in air: $$C_m = \frac{E}{\rho_m} \qquad (5)$$

Where E is Young's Modulus. If the radiation impedance has a reactive component this component acts as an additional mass "M" per unit volume which may be inserted in equation (5)

$$C_m = \frac{E}{P_m + M_c} \qquad (6)$$

This C_m is used in equation (3) to determine the resonant frequency. It is also used in equation (4) where in addition "ρc" must also be modified to a suitable fraction of its full value. The modifications mentioned can be scaled from experimental models. They vary with wall thickness, ring height and distance between rings.

The maximum acoustic output can be predicted by the method discussed by Ralph Woollett *Ref.

$$P_r = \eta \, \omega_r \, \frac{k^2}{1-k^2} \, Q_m \, V_e \qquad (7)$$

Where P_r is the power radiated at resonance per unit volume of active material, η the mechano-acoustic efficiency, ω_r, the angular frequency, k the electromechanical coupling coefficient, V_e the maximum magnetic energy density, and Q_m the mechanical quality factor. For nickel 204, the following values hold

$$\frac{k^2}{1-k^2} \, V_e = 400 \qquad (8)$$

APPENDIX 2

APPENDIX 2

f_r	...	Resonant frequency of vibrator in Hz
Q_{mw}	...	Mechanical quality factor in water
R	...	Series resistance of transducer in ohms
T	...	Transmit response in decibels per microbar for one ampere
Ω	...	Ohms
λ	...	Wave length

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